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ELEMENTS OF ENGINEERING GEOLOGY

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PREFACE

The importance of geology to engineering is constantly receiving wider and stronger recognition, for it is realized that whatever line of work the engineer is engaged in, whether highway construction, tunneling, quarrying, river and harbor improvement, water supply, mining, etc., he is almost certain to encounter problems of a geologic character. Indeed during the late European War, the importance of engineering geology to military operations came to be widely though tardily recognized. There has thus naturally developed an increased demand for instruction in geology as applied to engineering. The aim has been, therefore, to emphasize the practical application of the subjects treated in this volume to engineering work.

This volume is more than a condensation and simplification of a larger text "Engineering Geology" published by the authors in 1914, since it has involved complete rewriting of many parts of the larger book and the amplification of other parts. While "Engineering Geology" has met with a very gratifying reception, there are many institutions that desire a smaller volume to meet the requirements of a briefer course. It was to meet this demand that the present book was prepared.

ITHACA, N. Y., AND CHARLOTTESVILLE, VA.
January 1, 1921

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ELEMENTS OF ENGINEERING GEOLOGY

CHAPTER I

THE IMPORTANT ROCK-MAKING MINERALS

Introduction. — Of the eighty-odd elements known to the chemist, some are extremely rare, others are exceedingly abundant. Only sixteen enter largely into the composition of the outer solid portion of the earth so far as it is accessible to observation. Arranged in their order of abundance the percentages of these elements, as calculated by Professor F. W. Clarke, are:

Oxygen	47.33	Titanium	0.46
Silicon	27.74	Hydrogen	0.22
Aluminum	7.85	Carbon	0.19
Iron	4.50	Phosphorus	0.12
Calcium	3.47	Sulphur	0.12
Potassium	2.46	Barium	0.08
Sodium	2.46	Manganese	0.08
Magnesium	2.24	Chlorine	0.06

A few of these elements occur in nature uncombined in elemental form, but most of them are found only in combination forming compounds called minerals.

All rocks, with the exception of the glassy igneous ones, are composed of minerals, and since these minerals not only make up the rocks but vary greatly in their resistance to weather, it is necessary that we have a good knowledge of the characters and properties of the important rock-forming ones, in order to be able to identify rocks and to judge correctly their value.

The present chapter is devoted first, to an account of the general properties of the common rock-forming minerals that are of use in their megascopic determination, and second, to individual descriptions of the more important rock-forming minerals, with brief reference to their practical importance.

Definition of a mineral. — A mineral may be defined as any natural inorganic [1] substance of definite chemical composition. It is usually a solid, generally crystalline in structure but sometimes amorphous,[2] and may or may not occur bounded by crystal faces. As a rule external form is not developed in minerals as they occur in rocks, but usually as crystalline grains marked by irregular boundaries, because of interference with one another during growth. Crystalline grains are commonly referred to as *anhedrons*, signifying absence of crystal faces.

Altogether more than a thousand distinct mineral species are known; but the more common ones number less than thirty. This relatively small number of the large total of known minerals includes those which may be rated as the more abundant ones or as the essential components of rocks, hence they are aptly referred to as *rock-forming minerals*.

Definition of a crystal. — A crystal may be defined as a solid bounded by natural plane surfaces called *crystal faces*, symmetrically grouped about *axes*. By *axes* are meant imaginary lines which connect the centers of opposite faces, edges, or solid angles, and which intersect at some point within the crystal. Such a polyhedral form results when the molecules of a substance of definite chemical composition possess such freedom of movement as to arrange themselves according to mathematical laws, which results in internal crystalline structure and the outward expression of plane surfaces or faces. Under such conditions the minerals will usually crystallize with outward crystal form, such as cubes, octahedrons, prisms, etc. In the formation of rocks conditions sometimes favor definite arrangement of the molecules, and one or more of the minerals may assume outward crystal form, as shown in some igneous and metamorphic rocks.

The number of crystal forms is large and yet when they are grouped in their relations to crystallographic axes they fall into six systems. The names usually given to the six crystal systems and their axial relations are: *Isometric system.* Three axes of equal lengths and intersecting one another at right angles. *Tetragonal system.* Three axes intersecting at right angles, the two lateral axes being of equal length, while the vertical axis is longer or shorter than the two lateral ones. *Hexagonal system.* Four axes, the three laterals being of equal length and intersecting at angles of 60°, while the vertical axis is perpendicular to and longer or shorter than the three laterals. *Orthorhombic system.*

[1] Such organic substances as coal, amber, petroleum, asphalt, etc., are frequently included.

[2] Quite a number of minerals fail to show both crystal form and internal crystalline structure, when they are said to be *amorphous*. Opal and limonite are good examples.

Three axes intersecting at right angles and of unequal lengths. *Monoclinic system.* Three axes of unequal lengths, the two lateral ones at right angles to each other, while the vertical axis is oblique to one of the laterals. *Triclinic system.* Three axes of unequal lengths making oblique intersections with one another.

Twin crystals. — Crystals sometimes appear not to be simple or single forms but compound, in which one or more parts regularly arranged are in reverse position with reference to the other part or parts (Dana). This peculiar grouping is known as twinning, the different parts of such a crystal appearing as if revolved 180° about a line known as the *twinning axis.* The plane normal to the twin axis is called the *twinning plane*, and the plane of union of the two parts is called the *composition plane.* Many minerals frequently exhibit twinning, and in some it serves as an important means in determining them. Feldspars very often show several kinds of twinning, two of which are of importance in megascopic determinations, namely, Carlsbad and albite (multiple) twins (see Figs. 3 to 5). Multiple twinning is characteristic of the plagioclase or soda-lime feldspars, and affords the surest means of distinguishing them from orthoclase (see under *feldspar group*). Carlsbad twinning may be developed in any variety of feldspar, but is generally more frequent in orthoclase than in plagioclase.

General Physical Properties of Rock-making Minerals

The more important physical properties of rock-making minerals which are of value in their megascopic determination are *hardness, cleavage, luster, streak, color, tenacity, specific gravity,* and *crystal form.* These have not equal weight in determining minerals. The behavior of minerals before the blowpipe and with chemical reagents is an important means of determining them and forms that division of the subject known as determinative mineralogy.

Hardness. — Hardness is an important property of minerals and is of great value in their rapid determination. It may be defined as the resistance of a mineral to abrasion or scratching. The hardness of minerals is usually determined by comparing with Mohs's scale, which includes ten minerals arranged in the order of increasing hardness, as follows:

1. Talc; 2. Gypsum; 3. Calcite; 4. Fluorite; 5. Apatite; 6. Feldspar; 7. Quartz; 8. Topaz; 9. Corundum; 10. Diamond.

In testing the hardness of a mineral care must be taken to select a fresh fragment, and not mistake a scratch for a mark left by a soft mineral on the surface of a hard one. If an unknown mineral scratches

and in turn is scratched by a member of the scale, its hardness is the same as that of the scale member. Again if the unknown mineral scratches fluorite its hardness is greater than 4, but if it does not scratch apatite and is scratched by it, its hardness is between 4 and 5, or approximately 4.5.

In the absence of a scale, the hardness of a mineral may be approximated by use of the following materials: The finger nail will scratch gypsum (2), but not calcite (3); a copper coin will just scratch calcite (3); and the blade of an ordinary pocket knife will scratch apatite (5), but not feldspar (6).

Cleavage. — When properly tested most minerals exhibit more or less readiness to part along one or more definite planes. In most minerals possessing crystalline structure the molecules are so arranged that the force of cohesion is less along a particular direction or directions than along others. This property is called *cleavage.* It is a fairly constant property of minerals and is of great value in determining them. Cleavage always occurs parallel to possible crystal faces, and is so described. Thus we have cubic cleavage (galena), octahedral cleavage (fluorite), rhombohedral cleavage (calcite), prismatic cleavage (amphibole), basal cleavage (mica). All minerals do not possess cleavage, and comparatively few exhibit it in an eminent degree. Quartz and garnet do not show cleavage, but such minerals as feldspars, amphiboles, pyroxenes, and calcite are distinguished chiefly by their cleavage. The terms *perfect, imperfect, good, distinct, indistinct,* and *easy* are used to indicate the manner and ease with which cleavage is obtained.

Luster. — The luster of a mineral is the appearance of its surface in reflected light, and is an important aid in the determination of minerals. Two kinds of luster are recognized: *Metallic* luster, the luster of metals, most sulphides, and some oxides, all of which are opaque or nearly so; *nonmetallic* luster, the luster of minerals that are transparent on their thin edges, and in general of light color, but not necessarily so. The more common nonmetallic lusters are described as follows: *Vitreous,* the luster of glass; example quartz. *Resinous,* the appearance of resin; example sphalerite. *Greasy,* the appearance of oil; example some sphalerite and quartz. *Pearly,* the appearance of mother-of-pearl; example talc. *Silky,* the appearance of silk (satin), due to a fibrous structure; example satin spar and asbestos. *Adamantine,* the brilliant, shiny luster of the diamond. *Dull,* as in chalk or kaolin.

Streak. — By the streak of a mineral is meant the color of its powder. It is frequently one of the most important physical properties

to be applied in the determination of minerals, such as hematite and limonite. The color of a mineral in mass may vary greatly from that of its powder (streak, which is frequently fairly constant), and is usually much lighter. The streak may be determined by crushing, filing, or scratching, but the most satisfactory method is to rub the sharp point of a mineral over a piece of white, unglazed porcelain. Small plates, known as streak plates, are made especially for this purpose.

Streak is of most value in distinguishing between the dark-colored minerals like the metallic oxides and sulphides, and is of less value in discriminating between the light-colored silicate and carbonate minerals.

Color. — Color is one of the most important properties of minerals, and, when used with proper precaution, it is of great help in their rapid determination. The color of metallic minerals is a constant property; but it may vary greatly in many of the nonmetallic minerals, due to the presence of pigments or impurities, which may be either chemically combined or mechanically admixed. Even the metallic minerals, such as the sulphides (pyrite, marcasite and chalcopyrite) whose color is constant, are susceptible to tarnish (alteration), and a fresh surface should always be examined in noting the color.

The color of minerals is dependent upon their chemical composition, in which case it may be *natural*, or it may be due to some foreign substance distributed through them and acting as a pigment, and their color may then be termed *exotic* (Pirsson). Precaution should be used, therefore, in the latter case when color is employed in the determination of minerals.

The introduction of the metallic oxides, the commonest one of which is iron, will influence the color, and according to its quantity the mineral will ordinarily exhibit some shade of green, brown, or even black. Examples among the silicate minerals are the iron-bearing members of the amphibole, pyroxene, and mica groups.

Exotic color may result (1) from the presence of a very small amount of some compound in chemical combination, such as manganese oxide in quartz imparting an amethyst color; or (2) mechanically admixed impurities such as small amounts of hematite in quartz producing the red variety jasper.

Tenacity. — Tenacity relates to the behavior of a mineral when an attempt is made to break, hammer, cut, bend, or crush it. The well known terms brittle, malleable, sectile, tough, flexible, elastic, etc., are used in describing minerals. A mineral is *brittle* when it breaks or powders easily, *malleable* when it flattens under the hammer, *sectile* when it can be cut but crumbles when hammered, *tough* when its resistance to tear apart under a blow or strain is great, *flexible* when

it bends and remains bent after the pressure is released, *elastic* when bent it recovers its original position upon release of pressure. Quartz is brittle; gold, malleable; talc, sectile; chlorite, tough and flexible; and mica, elastic.

Specific gravity. — The specific gravity of a mineral is its weight compared with that of an equal volume of water. In a pure mineral of given composition, it is a constant factor, and is an important aid in identification. The specific gravity of most silicate minerals lies between 2.25 and 3.5; of minerals with metallic luster usually between 4.5 and 10; and of natural-occurring metals as high as 23 (iridium).

As ordinarily carried out in the laboratory, the determination of the specific gravity of a mineral is made as follows: The fresh mineral is first weighed in air, which value we may call x. It is then immersed in water and weighed again, and the value may be called y. Then $x - y$ equals the loss of weight in water, or the weight of an equal volume of water. We then have

$$G = \frac{x}{x - y}, \ G \text{ being the specific gravity.}$$

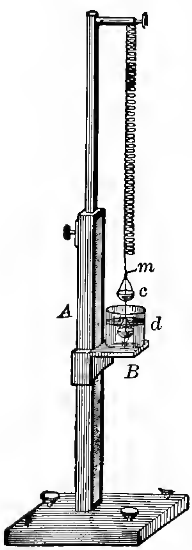

FIG. 1.

The determination of specific gravity may be carried out on several different kinds of balances, but one of the most convenient forms is the Jolly balance, shown in Fig. 1. The time required for the whole determination on this balance should not exceed several minutes.

Crystal form. — Minerals are usually developed in rocks as crystalline grains without definite shape rather than as distinct crystals. Exceptions to this are the phenocrysts in porphyritic rocks (p. 41), some minerals formed in rocks by replacement (p. 329), and minerals lining cavities in rocks. When minerals exhibit definite shapes crystal form becomes an important aid in their determination. Because of the fact, however, that minerals composing rocks are more often developed without crystal boundaries, crystal form is less important as an aid in determining them than other physical properties.

Fracture. — When a mineral breaks irregularly without regard to definite direction it is described as fracture. The appearance of a fracture surface is somewhat characteristic and is commonly designated by the following terms: *Conchoidal,* when the surface presents a somewhat shelly appearance; *fibrous* or *splintery,* when the surface

shows fibers or splinters; *hackly*, when the surface is irregular with sharp edges; *uneven*, when the surface is rough and irregular.

Other physical properties of minor importance but nevertheless useful at times in the determination of minerals are *taste, odor, feel* or *touch*, and *magnetism*.

Chemical tests. — Since chemical composition is the most fundamental property of minerals, chemical tests with dry and wet reagents form the safest and most satisfactory means of identification. The common rock-forming minerals, however, can usually be readily and quickly determined by their physical properties, and since the equipment of a laboratory is not available in the field, it is essential that a thorough knowledge of the physical properties of minerals be obtained. Tables employing both physical and chemical tests for the determination of minerals are to be found in a number of excellent manuals on determinative mineralogy.

Description of Rock-forming Minerals

The number of known minerals is large; but only a few are of importance as rock-makers. The principal ones from the geological standpoint may be grouped chemically as silicates, oxides, carbonates, sulphates, and sulphides, under which in the order named the individual minerals are treated.

Silicates

The silicates are the most important rock-forming minerals, since they compose a large part of the earth's crust. They are salts of silicic acids, many being of complex composition. Those of most importance as rock-forming minerals are the feldspar, pyroxene, amphibole, mica, olivine, garnet, tourmaline, and epidote groups.

For convenience of treatment the silicates may be divided into A. Anhydrous silicates, and B. Hydrous silicates.

A. Anhydrous Silicates

Feldspar

General properties. — The important rock-making feldspars are silicates of alumina, together with potash, soda, or lime, or their mixtures. They include (1) the potash feldspars *orthoclase* and *microcline* ($KAlSi_3O_8$), (2) the soda feldspar *albite* ($NaAlSi_3O_8$), and (3) the lime feldspar *anorthite* ($CaAl_2Si_2O_8$); (4) mixtures of 1 and 2, *alkalic* feldspar, and (5) mixtures of 2 and 3, *plagioclase* or soda-lime feldspars.

Feldspar may be monoclinic (orthoclase) or triclinic (microcline and

plagioclase) in crystallization, but perfect crystals (Fig. 2) are rarely observed, except when developed as phenocrysts in porphyritic igneous rocks (see Chapter II). Usually the feldspars develop as formless

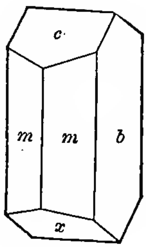

FIG. 2.

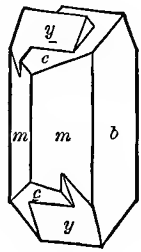

FIG. 3.

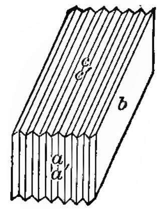

FIG. 4.

grains. Twinning is common in the feldspars (Figs. 3 to 5) and is an important means of distinguishing between orthoclase and plagioclase varieties. Figure 3 shows an orthoclase twin. The polysynthetic twinning (Figs. 4 and 5) of plagioclase is indicated by fine parallel striations on the cleavage surfaces. All species of feldspar possess good cleavage in two directions, which intersect at 90° in orthoclase and at about 86° in plagioclase. Their hardness is 6; specific gravity 2.55–2.76. Luster vitreous; pearly on cleavage faces. Color variable, colorless and glassy feldspars being limited to fresh and recent lavas. Orthoclase is commonly red, while plagioclase is commonly gray or white. Feldspar is often the dominant coloring mineral in granites.

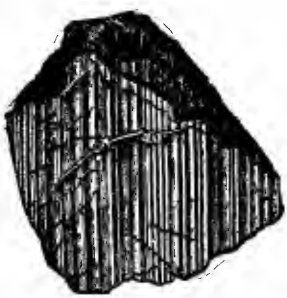

FIG. 5.

Alteration. — Feldspars commonly alter to kaolinite in the belt of weathering, when acted on by water containing carbon dioxide, with the separation of free silica and alkaline carbonates. The lime-bearing species on alteration may yield calcite. Potash feldspar, under conditions of dynamic metamorphism (see Chapter III), or by hydrothermal metamorphism, commonly alters to sericite (p. 9). The change of feldspar to kaolinite, known as *kaolinization*, is first noted in the feldspars by loss of luster, the mineral becoming dull and chalky or earthy in appearance. Lime-soda feldspars are more susceptible to alteration than orthoclase, and both are less durable than quartz, with which they are frequently associated, but they are not to be regarded as unsafe in building stones on that account.

The changes involved in the alteration of feldspar to kaolinite and muscovite have been expressed chemically as follows:

$$\overset{\text{Orthoclase}}{2\,KAlSi_3O_8} + \overset{\text{Water}}{2\,H_2O} + \overset{\text{Carb. diox.}}{CO_2} = \overset{\text{Kaolinite}}{H_4Al_2Si_2O_9} + \overset{\text{Quartz}}{4\,SiO_2} + \overset{\text{Potas. carb.}}{K_2CO_3}$$

$$\overset{\text{Orthoclase}}{3\,KAlSi_3O_8} + \overset{\text{Water}}{H_2O} + \overset{\text{Carb. diox.}}{CO_2} = \overset{\text{Muscovite}}{H_2K(AlSiO_4)_3} + \overset{\text{Quartz}}{6\,SiO_2} + \overset{\text{Potas. carb.}}{K_2CO_3}$$

Occurrence. — Feldspars are probably more widely distributed than any other group of rock-forming minerals. They occur in most of the igneous rocks, such as granites, syenites, and lavas; in certain sandstones (*arkoses*) and conglomerates among sedimentary ones; and in gneisses and other metamorphic rocks. Hence feldspar is an important constituent of many building stones. The feldspar of commerce is obtained from pegmatites (p. 44).

Mica

General properties. — The micas form a group of silicate minerals of complex composition. For megascopic study they may be divided into (1) *light* colored micas represented by *muscovite* ($H_2KAl_3(SiO_4)_3$), the potash mica, and (2) *dark* colored micas, represented by biotite ($(K,H)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$), the iron-magnesium mica. They crystallize in the monoclinic system in tabular crystals having flat bases, and often of hexagonal outline. Although crystals are observed in rocks, the micas usually occur in flakes, scales, or shreds, sometimes bent or curved, with shining cleavage faces. All micas are characterized by perfect basal cleavage, along which they may split into extremely thin elastic plates or leaves, that are tough and flexible. This property, combined with transparency, toughness, and flexibility, makes the large sheets of muscovite of considerable commercial value. The color of micas varies, dependent chiefly on chemical composition. *Muscovite* is colorless, white to gray, sometimes greenish to light brown, while *biotite* is usually brown to black, sometimes dark green. The color of mica frequently exerts an important effect on building and ornamental stones containing it. Hardness 2–3; easily scratched with the knife; specific gravity 2.7–3.2. Luster vitreous to pearly or silky.

Alteration. — Muscovite is very resistant to weathering processes, but it probably alters ultimately to clay. By the action of heated vapors and water feldspars may be changed into muscovite of silky luster, known as the variety *sericite*, and this process of formation

[1] Kaolin may sometimes be formed in other ways. See Ries "Clays, Their Occurrence, Properties, and Uses," Wiley & Sons, Inc., New York.

termed *sericitization* has occurred in many ore deposits. Biotite, on account of its iron content, alters more readily, the commonest products of alteration being chlorite and iron oxides. The alteration of biotite in some building stones may cause unsightly coloration at times from the liberation of iron oxide. This is frequently observed in natural outcrops of many granites, and in opening a new quarry failure to strip the stone below the depth of oxidation may result in placing an inferior stone (sappy granite) on the market.

Occurrence. — The common micas, *muscovite* and *biotite*, have wide distribution in igneous and metamorphic rocks and in some sedimentary ones, especially sandstones. *Muscovite* is a common constituent of the more acid igneous rocks, like granites and their pegmatites, from which latter commercial mica is ordinarily derived, and is an abundant mineral in metamorphic rocks, especially crystalline schists and gneisses. *Biotite* occurs in many granites, diorites, gabbros, and peridotites, and their fine-grained equivalents, and in crystalline schists and gneisses.

The presence of mica in building stones may exert an important influence on their durability and workability. When present in abundance and the shreds have parallel arrangement, the rock may split readily along this direction. In quantity, mica is an undesirable constituent of marble, because it is apt to weather out leaving pitted surfaces, and at times interferes with the production of a good polish. Although some building stones, such as granite, etc., are rarely free from mica, it is not an injurious constituent unless present in large quantity, or segregated into large and small areas through the stones as "knots," rendering the rock unsightly and therefore undesirable for some uses.

Pyroxene

General properties. — The pyroxenes form an important group of rock-making minerals which, like the amphiboles, are salts of metasilicic acid (H_2SiO_3). The more important rock-making members of the group are: *Enstatite* ($MgSiO_3$); *hypersthene* ($(MgFe)SiO_3$); *diopside* ($CaMg(SiO_3)_2$) with little or no ferrous iron; and *augite*, which is more complex and in addition contains alumina and ferric iron. Pyroxenes are orthorhombic, monoclinic, or triclinic in crystallization, but members of the triclinic system are of no importance as rock-forming minerals. They all agree in general crystal habit, a prism with an angle of about 87° and 93°;

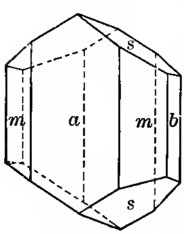

Fig. 6.

usually short, stout, prismatic (Fig. 6), or columnar. A cross section of the prism form is usually octagonal in outline (Fig. 7). (Compare with cross section of amphibole, Fig. 8.) Pyroxenes are also commonly developed in shapeless grains and masses.

All pyroxenes show cleavage developed in two directions parallel to the prism faces, intersecting at an angle of 87° (Fig. 7). The cleavage angle is a fundamental property and serves to distinguish pyroxenes from amphiboles. Hardness 5–6; specific gravity 3.2–3.6. Color varies according to the iron content; white to gray and pale-green in *enstatite* and *diopside;* dark brown to greenish brown in *hypersthene;* and various shades of green to black in *augite.* Luster vitreous to resinous and pearly.

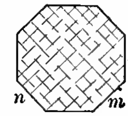

Fig. 7.

Alteration. — Under the action of weathering agents pyroxenes commonly alter into serpentine and chlorite, accompanied at times by carbonates and iron oxides. Under conditions of dynamic metamorphism pyroxenes alter into amphiboles.

Occurrence. — The pyroxenes are chiefly found in igneous rocks, especially the basic ones, such as basalts, gabbros, and peridotites (see Chapter II). They are less common in metamorphic rocks, being noted in some crystalline limestones and gneisses, but are rare in sedimentary rocks. They are not very important in the common building stones, and when present in quantity and of the brittle variety, they may interfere with the production of a smooth polish.

Amphibole

General properties. — The amphibole group of minerals is parallel to the pyroxene group, the two groups having similar chemical composition and physical properties. Both groups are salts of metasilicic acid (H_2SiO_3), but the amphiboles differ from the pyroxenes mainly in the prism and cleavage angle which is 125° and 55° instead of 87°. For megascopic purposes the more important varieties of amphibole are: *Tremolite* ($CaMg_3(SiO_3)_4$); *actinolite* ($Ca(MgFe)_3(SiO_3)_4$); and *hornblende,* which is more complex in composition but contains also alumina and ferric iron.

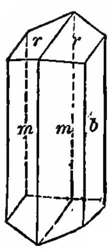

Fig. 8.

Amphiboles may be orthorhombic, monoclinic, or triclinic in crystallization, but only the monoclinic members are of megascopic importance as rock-making minerals. All agree in general habit and in having a prismatic cleavage of 55° and 125°. They generally occur in long and bladed forms (Fig. 8), sometimes fibrous and columnar, and in shapeless grains and masses. The outline cross-section

of the prism form is usually hexagonal (Fig. 9). Cleavage in two directions parallel to the cleavage faces intersecting at angles of 55° and 125°. The cleavage angle is one of the most distinguishing characteristics of the amphiboles. Compare Fig. 9 showing cleavage of amphibole with Fig. 7 which shows cleavage of pyroxene. Hardness 5–6; specific gravity 2.9–3.5, according to the amount of iron present. Color varies according to the iron content from white or gray in *tremolite* to light green in *actinolite* to dark green and black in *hornblende*. Luster vitreous to pearly on cleavage faces, often silky in fibrous varieties.

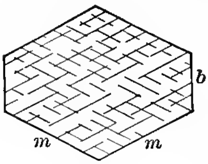

FIG. 9.

Alteration. — Under conditions of weathering amphiboles commonly alter, according to composition, into chlorite or serpentine usually accompanied by carbonates, quartz, and epidote. They may finally break down into carbonates, iron oxides, and quartz.

Occurrence. — Amphiboles are important rock-making minerals and occur in a variety of igneous and metamorphic rocks. *Tremolite* and *actinolite* are metamorphic minerals, the former occurring chiefly in crystalline limestones and the latter in crystalline schists. They may also occur as products of alteration in igneous rocks. Owing to its tendency to decompose, *tremolite* is a harmful mineral in crystalline dolomitic limestones. *Hornblende* occurs both in igneous and metamorphic rocks, and when derived from pyroxene by metamorphism, it is known as the variety *uralite*.

Garnet

Physical properties. — Garnet corresponds to the general formula $R_3''R_2'''(SiO_4)_3$,[1] the most common varieties of importance as rock-forming minerals being: *Grossularite* ($Ca_3Al_2(SiO_4)_3$); *pyrope* ($Mg_3Al_2(SiO_4)_3$); *almandite* (common garnet, ($Fe_3Al_2(SiO_4)_3$); and *andradite* ($Ca_3Fe_2(SiO_4)_3$). Garnet crystallizes in the isometric system, commonly as dodecahedrons (Fig. 10) and trapezohedrons (Fig. 11). It often occurs in rocks as formless grains and granular aggregates of rounded or irregular outline. Hardness 6.5–7.5; specific gravity 3.15–4.3, varying with the composition, common garnet being 4.0. Color varies

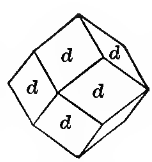

FIG. 10.

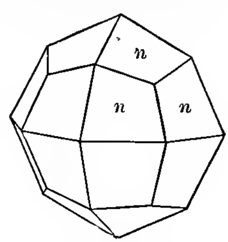

FIG. 11.

[1] $R_3'' =$ Ca,Mg,Fe,Mn; $R_2''' =$ Al,Fe,Cr, etc.

according to composition: *Grossularite*, white to pale shades of pink, yellow, and brown; *pyrope*, deep red to nearly black; *almandite*, deep red to brownish-red; and *andradite* is black. Luster vitreous.

Alteration. — Dependent upon composition, garnet may alter to chlorite or serpentine, less often to hornblende. Chlorite is the commonest alteration product of common garnet, and limonite is a common end product in the alteration of the iron-bearing varieties.

Occurrence. — Garnet is found chiefly in metamorphic rocks and, to a less extent, in some igneous ones. *Grossularite* is chiefly found in crystalline limestones; *pyrope* in some basic igneous rocks, especially peridotites; *almandite* in crystalline schists or gneisses, sometimes in pegmatites, and in contact metamorphic zones; while *andradite* is restricted to some basic igneous rocks and contact-metamorphic deposits. The principal use of garnet is as an abrasive.

Olivine

General properties. — Olivine (*chrysolite*) corresponds to the general formula Mg_2SiO_4, in which magnesium may be replaced by more or less ferrous iron. It crystallizes in the orthorhombic system, but distinct crystals are rare, since its common occurrence in rocks is as formless grains and granular masses. Cleavage indistinct; fracture conchoidal. Hardness 6.5–7; specific gravity 3.27–3.37. Color olive to yellow green, but bottle green very common. Luster vitreous. Olivine commonly alters to serpentine and iron oxide.

Occurrence. — Olivine is a characteristic mineral of the less siliceous igneous rocks, such as gabbros, peridotites, and basaltic lavas, but it also occurs in metamorphosed magnesian limestones and some schists.

Epidote

General properties. — Epidote, a basic orthosilicate of calcium and aluminum with variable iron, is monoclinic in crystallization, but crystal form is of little importance, since it commonly occurs in rocks in formless grains and granular aggregates. Cleavage unequally developed in two directions. Hardness 6–7; specific gravity 3.3–3.5. Color usually some shade of green, yellowish green being the most common. Luster vitreous.

Occurrence. — Epidote occurs abundantly as a secondary mineral in igneous rocks, derived from the alteration of ferromagnesian minerals and lime-soda feldspars, and commonly accompanies chlorite. It has a similar occurrence in crystalline schists and gneisses. It may be abundant in some limestones altered by contact metamorphism.

Tourmaline

General properties. — Tourmaline is a complex silicate of aluminum, boron, iron, magnesium, and the alkalies. It crystallizes in the rhombohedral division of the hexagonal system in short to long prismatic forms (Fig. 12), three-, six-, or nine-sided, the prism faces being often vertically striated. Triangular cross-section of the prism form (Figs. 13 and 14) is especially characteristic of rock-making tourmaline.

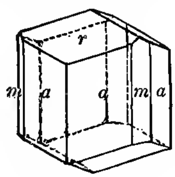

FIG. 12.

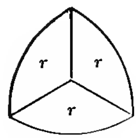

FIG. 13.

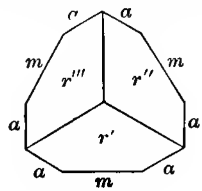

FIG. 14.

(Compare with pyroxene (Fig. 7) and amphibole (Fig. 9).) Tourmaline also occurs in shapeless grains and masses. It has a hardness of 7–7.5; specific gravity 2.98–3.20. Color variable, but the common rock-making variety is black. Luster vitreous. Tourmaline is very resistant to weather.

Occurrence. — Tourmaline is a widely distributed constituent of the crystalline schists and of the more acid igneous rocks, such as granites and their accompanying pegmatites. It also occurs in some gneisses and clay slates, and is a common mineral of contact metamorphic zones. It is sometimes used as a gem mineral.

B. HYDROUS SILICATES

Of the hydrous silicates *kaolinite*, *talc*, *serpentine*, and *chlorite* are the most important rock-making minerals. These are of secondary origin, and may be formed either by weathering or by heated circulating waters or vapors acting on rock masses. They are of most importance in sedimentary and metamorphic rocks, and are of no importance in fresh igneous rocks. They occur as constituents in the wall rock of many ore deposits formed by the alteration of original silicate minerals by different geologic processes (see Chapter on Ore Deposits).

Kaolinite

General properties. — Kaolinite ($H_4Al_2Si_2O_9$) crystallizes in the monoclinic system as minute scales or plates with sometimes hexagonal outlines, but crystal form is of no value in megascopic determinations. It may occur in clay-like masses, or scattered irregularly through feldspathic rocks. Its color is white, but it is often colored by impuri-

ties. Luster usually dull, earthy. Hardness 1–2.5; specific gravity 2.2–2.63. Neither hardness nor gravity is serviceable for practical tests. It usually has an unctuous, greasy feel, and is plastic when wet.

Occurrence. — Kaolinite has widespread occurrence, and is a common constituent of clay. It is always a secondary mineral, formed usually by the weathering of aluminous silicate minerals, chiefly feldspars. The chemical equation showing derivation of kaolinite from orthoclase by weathering (*kaolinization*) is given under feldspar, page 9. By it rock-masses are decomposed and soils are formed. Extensive deposits often result from the alteration of aluminous rocks and, when not discolored by iron oxide and other impurities, form the sources of white ware and paper clays. Deposits of clay of variable thickness and extent, showing all degrees of admixture with sand, etc., and discolored by impurities, occur. Masses of sericite are sometimes mistaken for kaolinite.

Talc

General properties. — Talc ($H_2Mg_3(SiO_3)_4$) commonly occurs in foliated masses, compact, and fibrous. Its crystal form is doubtful. Two varieties are usually recognized: (1) *Foliated talc* having light green to white color, a pronounced greasy feel, and foliated structure, used in paper manufacture, as a toilet powder, filler in cloth, etc.; and (2) *steatite* or *soapstone*, an impure talc of greenish color and massive granular in structure, extensively used for sinks, laundry tubs, etc. Talc has perfect basal cleavage like mica; the laminæ though flexible are inelastic. Hardness 1; specific gravity 2.6–2.8. Color white to greenish or gray. Luster pearly; soapy or greasy feel.

Occurrence. — Talc is derived by alteration from non-aluminous magnesian silicates, such as olivine, enstatite, tremolite, etc. Its derivation from enstatite may be represented chemically as follows:

$$\underset{\text{Enstatite}}{4\,MgSiO_3} + \underset{\text{Water}}{H_2O} + \underset{\text{Carb. diox.}}{CO_2} = \underset{\text{Talc}}{H_2Mg_3(SiO_3)_4} + \underset{\text{Magnesite}}{MgCO_3}$$

It may occur as an alteration product of basic igneous rocks, such as peridotites and pyroxenites, but it is of chief importance in the metamorphic rocks, such as talc schists and soapstone or steatite. (See further under metamorphic rocks.)

Serpentine

General properties. — Serpentine ($H_4Mg_3Si_2O_9$) does not crystallize but usually occurs compact or granular massive and often fibrous, the fibers being flexible and easily separated from each other. *Ordi-*

nary serpentine is massive, opaque, and of various shades of green, while *chrysotile* is the fibrous or asbestiform variety occurring in veins in massive serpentine and, for the most part, is the *asbestos* of commerce. *Precious serpentine*, the massive, translucent, light to dark green variety, is often mixed with calcite or dolomite and shows variegated coloring, when it is called *verd antique* marble, or *ophicalcite*. The color of serpentine is usually some shade of green, yellow, or red, and black, but often variegated showing mottling in lighter and darker shades of green. Luster is greasy and wax-like in the massive varieties and silky in the fibrous. It has a greasy feel and is translucent to opaque. Hardness varies, but is usually 4; specific gravity, 2.2–2.8.

Occurrence. — Serpentine is a secondary mineral formed as an alteration product from magnesian silicates, such as olivine, pyroxene, and amphibole in igneous and metamorphic rocks. Its derivation from olivine may be shown chemically as follows:

$$\underset{\text{Olivine}}{2\,Mg_2SiO_4} + \underset{\text{Water}}{2\,H_2O} + \underset{\text{Carb. diox.}}{CO_2} = \underset{\text{Serpentine}}{H_4Mg_3Si_2O_9} + \underset{\text{Magnesite}}{MgCO_3}.$$

Serpentine is an important constituent of the verd antique marbles (ophicalcite), used as an ornamental stone in decoration and building. (See p. 108.)

Chlorite

General properties. — Chlorite is a general name for a group of minerals that cannot usually be distinguished from each other by the naked eye. The chlorites are hydrous silicates of aluminum with ferrous iron and magnesium. Like mica, they are monoclinic in crystallization, but distinct crystals are rare and they commonly occur in rocks as flakes, scales and scaly masses. They have perfect basal cleavage, yielding foliæ which are tough, but unlike mica are inelastic. Color green of various shades, usually dark green. Luster vitreous to pearly. Hardness 1–2.5; specific gravity 2.65–2.96.

Occurrence. — Chlorite is a common secondary mineral in many igneous and metamorphic rocks, or even some sedimentary ones, formed chiefly by the alteration of aluminous ferromagnesian silicates, such as pyroxene, amphibole, mica, etc. The green color of many basic igneous rocks, such as traps and basalts, and of many metamorphic rocks, such as schists and slates, is due to the presence of chlorite. It is a common product of hydrothermal action along some ore bodies.

Oxides

The more important rock-making minerals among the oxides are *quartz* (SiO_2), *corundum* (Al_2O_3), and the *iron ores*, including *magnetite* (Fe_3O_4), *ilmenite* ($FeTiO_3$), *hematite* (Fe_2O_3), and *limonite* ($2\ Fe_2O_3 \cdot 3\ H_2O$).

Quartz

General properties. — Quartz (SiO_2) crystallizes in hexagonal prisms capped by pyramidal faces (Figs. 15 and 16), but, except when formed in cavities and as phenocrysts in some igneous rocks (porphyries), crystal form is not often observed. Its usual occurrence in rocks is as shapeless grains and masses. It has no cleavage, which helps to distinguish quartz from feldspar. The color varies widely from white or colorless to almost any color. Luster vitreous to greasy. Hardness 7; specific gravity 2.65. Transparent to opaque. *Chalcedony*, *flint* or *chert*, and *jasper*, composed usually of a mixture of crystalline and non-crystalline silica, are varietal forms of quartz. Chert is not uncommon in some limestones, and is an undesirable constituent if the rock is to be used for building stone, lime, or cement. Quartz is a very resistant mineral to weathering and is altered chiefly by physical (disintegration) rather than by chemical (decomposition) agents.

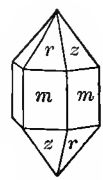

FIG. 15.

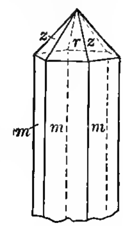

FIG. 16.

Occurrence. — Quartz is one of the commonest of minerals and is found in igneous, sedimentary, and metamorphic rocks. It is an important constituent of granites and related igneous rocks; of quartzites, schists, and gneisses; and of many sands and sandstones. It may occur as veins in many different rocks, and, is the most common gangue mineral of ore deposits.

Corundum

General properties. — Corundum (Al_2O_3) is hexagonal-rhombohedral in crystallization, the crystals being usually prismatic or tapering hexagonal pyramids. It also occurs as grains and shapeless masses. It has basal and rhombohedral parting resembling cleavage, and is next in hardness (9) to diamond. Specific gravity 4. Adamantine to vitreous luster. Color of rock-making variety is usually gray to bluish-gray or smoky. Translucent to opaque. It is a resistant mineral to weathering. *Emery* is a fine-grained corundum mixed with other minerals, chiefly magnetite, and like corundum is used as an abrasive. Certain clear varieties of corundum are of value as gems.

Occurrence. — Corundum occurs in some alumina-rich igneous rocks, such as syenites and peridotites, in some crystalline schists and metamorphosed limestones, and in contact-metamorphic zones.

Iron Oxides

The important iron ore minerals among the oxides that have value as rock-making ones are *magnetite, ilmenite, hematite,* and *limonite.* Although widely distributed as frequent constituents of rocks these minerals occur chiefly as accessory ones, and are therefore not so important as the more important silicate minerals, such as feldspar, mica, amphibole, pyroxene, etc. They frequently form large bodies of commercial value concentrated by geologic processes, and excepting ilmenite, constitute the main sources of the ore for the metal iron.

Magnetite

Physical properties. — Magnetite (Fe_3O_4) crystallizes in the isometric system commonly as octahedrons and dodecahedrons (Figs. 17 and 18). It may also occur as formless grains. Cleavage not distinct. Color and streak black; luster metallic. Opaque and strongly magnetic. Hardness 5.5–6.5; specific gravity 5.17. Alters principally to hematite and limonite.

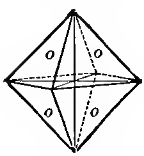

FIG. 17.

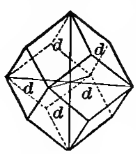

FIG. 18.

Occurrence. — Magnetite is a common accessory mineral in igneous and metamorphic rocks and in some sedimentary ones. It is an important ore of iron when it forms ore bodies of several different kinds, sometimes of large size (Chapter XII). It is of little importance in building stones, except in slates for electrical work, where it may do harm.

Ilmenite

Physical properties. — Crystals (hexagonal-rhombohedral) of ilmenite ($FeTiO_3$) are not often observed in rocks, but the mineral usually occurs in grains and masses and often in thin plates. Cleavage indistinct. Hardness, 5–6; specific gravity, 4.3–5.5. Opaque. Luster metallic. Color and streak black. Sometimes magnetic. Infusible and not acted on by acids.

Occurrence. — Ilmenite is a common mineral in igneous and metamorphic rocks, its mode of occurrence in these being similar to that of magnetite, from which it cannot usually be distinguished by the naked eye, except when one or the other shows crystal form. Its most important occurrence is as segregations in gabbros. Its principal use is as a source of titanium in the manufacture of ferrotitanium alloys.

Hematite

General properties. — Hematite (Fe_2O_3) as a rock-making mineral rarely occurs in distinct crystals (hexagonal-rhombohedral), but is found in several forms, the more important ones of which are *specular* and *common red* hematite. Specular hematite usually occurs in crystalline micaceous scales, grains, and masses of steel gray to black color with metallic luster, while common red hematite is generally found massive, granular to compact, sometimes in rounded forms, and earthy, of dark red color and dull luster. The red streak of hematite distinguishes it from limonite. Hardness 5.5–6.5; specific gravity 4.9–5.3. Color steel-gray to black and deep red. Opaque. It alters principally to limonite on exposure to weather.

Occurrence. — Hematite is a widely distributed mineral in igneous, sedimentary, and metamorphic rocks, and is the principal ore mineral of iron, since it supplies more than 80 per cent of the total annual production of iron ores in the United States (Chapter XII). It is a common alteration product of many iron-bearing minerals.

Limonite

General properties. — Limonite ($2\,Fe_2O_3 \cdot 3\,H_2O$) does not crystallize but occurs in earthy masses in rocks, and in stalactitic, compact, fibrous, concretionary, and earthy forms. It has no cleavage, and is usually dull or earthy to submetallic in luster. The color is usually some shade of brown or brownish yellow. Streak yellow-brown and very characteristic, which serves to distinguish it from hematite. Hardness about 5 in the compact varieties; specific gravity 3.6–4.

Occurrence. — Limonite is a secondary mineral formed by the weathering and alteration of other iron-bearing compounds. It is frequently noted in igneous and metamorphic rocks derived from original iron-bearing minerals, especially pyrite; as the cap (*gossan*) of many sulphide ore bodies; in beds and irregular bodies forming residual deposits from iron-bearing rocks; as loose, porous, and earthy masses known as *bog iron ore*, deposited in swamps and other shallow water bodies; and as the coloring matter in many soils, clays, and other sedimentary rocks, and is a common cement of many. Limonite is a valuable ore mineral of iron, and ranks next to hematite in importance in the United States (Chapter XII).

Carbonates

The carbonates, *calcite, dolomite,* and *siderite* are secondary minerals formed by weathering of other minerals or derived from deeper sources within the earth. They may be deposited in place or else carried in

solution by water containing carbon dioxide into seas and lakes and precipitated by organic agents, as limestone, etc.

Calcite

General properties. — Calcite ($CaCO_3$), one of the most important minerals geologically, often occurs in well-defined crystals (hexagonal-rhombohedral, Figs. 19, 20, and 21), but as a rock-making mineral it usually occurs fine to coarse crystalline granular in marble; compact in ordinary limestone; loose and earthy in chalk; spongy in tufa; and stalactitic in cave deposits. It has perfect rhombohedral cleavage in three directions which intersect at angles of 75° and 105° (Fig. 21). Hardness 3; specific gravity 2.72. Colorless or white, but frequently exhibits a variety of color from impurities. Luster vitreous to earthy. Transparent to translucent, and opaque when impure. Strong double refraction.

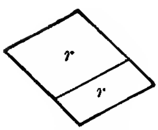

FIG. 19.

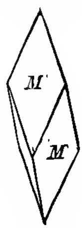

FIG. 20.

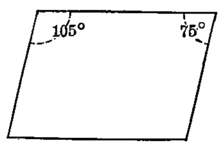

FIG. 21.

Occurrence. — Calcite is an abundant constituent of calcareous sedimentary and metamorphic rocks. Many limestones, chalk, bog limes and tufas, cave deposits, and marbles are composed almost entirely of calcite. It is a common vein mineral and also occurs in many igneous rocks where it is formed from the alteration of lime-bearing silicate minerals. It is readily distinguished from dolomite by effervescing freely in cold dilute acid.

Dolomite

General properties. — Dolomite ($CaMg(CO_3)_2$), like calcite, is found in rhombohedral crystals, whose faces are often curved (Fig. 22), but as a rock mineral it usually occurs massive, frequently crystalline granular, as in some marbles. It has rhombohedral cleavage in three directions, which intersect at angles of nearly 74° and 106°. Hardness 3.5–4; specific gravity 2.85. Color variable from impurities but usually pink, white, or gray. Luster vitreous or pearly.

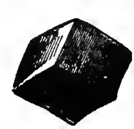

FIG. 22.

Occurrence. — Dolomite occurs principally in sedimentary and metamorphic rocks, such as limestones and marbles. In these it may often be intimately mixed with calcite in varying proportions. Lack of free effervescence in cold dilute acid distinguishes it from calcite.

Siderite

Siderite ($FeCO_3$) like calcite and dolomite crystallizes in the hexagonal system, the crystals being usually rhombohedrons. The most frequent form is in cleavable, granular compact earthy masses, or concretions. Hardness 3.5–4. Specific gravity 3.8. Color usually light to dark brown, sometimes black from included carbonaceous matter. Luster, vitreous to pearly. It alters to limonite in the belt of weathering, and to hematite and magnetite under deeper seated conditions.

Siderite is an important rock-making carbonate in many sedimentary rocks. Concretions with clayey impurities are called *clay ironstone.* Beds of it with much carbonaceous and argillaceous matter are called *black band ore,* and both may serve as low grade iron ores.

Sulphates

Like the carbonates, the rock-making sulphates, *gypsum* and *anhydrite,* are secondary minerals, derived from preëxisting ones. They are carried as soluble salts to the sea and lakes where, under proper climatic conditions, they are precipitated on concentration by evaporation (see Chapter on Rocks).

Gypsum

Physical properties. — Gypsum ($CaSO_4 . 2\ H_2O$) is sometimes found in good crystals of monoclinic form (Fig. 23), but as a rock constituent it occurs as foliated masses with curved faces, granular to compact, and fibrous. The common varieties are *selenite,* in crystals or foliated masses; *satin spar,* fibrous in structure with silky luster; *alabaster,* a fine-grained white variety; and *rock gypsum,* which is massive, granular, or earthy, often impure. Gypsum has one perfect cleavage by which it may be split into thin sheets, and a second less perfect cleavage. Hardness 1.5–2; specific gravity 2.32. Colorless or white, but often tinted other shades by impurities. Luster vitreous, silky, or pearly. Transparent to translucent and opaque.

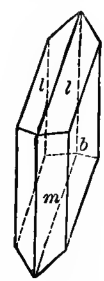

FIG. 23.

Occurrence. — Gypsum frequently forms more or less extensive beds and lenses in sedimentary rocks, especially limestones and clays, and has probably formed chiefly by the evaporation of inland seas. Some shales and clays contain scattered grains, crystals and concretions of gypsum, and it is occasionally found in veins. It is often associated with anhydrite and rock salt. Its chief use is for plaster (Chapter II).

Anhydrite

Physical properties. — Anhydrite ($CaSO_4$) is rarely found in orthorhombic crystals, but usually occurs in rocks in granular or compact masses, less often in foliated or fibrous form. It has three directions of cleavage, intersecting at right angles. Hardness 3–3.5; specific gravity 2.95. Color same as gypsum; luster pearly on cleavage faces.

Occurrence. — Anhydrite occurs as beds, lenses, irregular masses and veins in sedimentary rocks, and is frequently associated with gypsum and rock salt. Its appreciably greater hardness than gypsum is readily observed by the driller and quarryman.

Sulphides

The sulphides form an important group of ore minerals (see Chapter on Ore Deposits), but on account of their usual sparing occurrence in rocks, *pyrite* is the only one that has any special importance as a rock-forming mineral. When present to any extent in rocks used for building and ornamental purposes, the sulphides of iron are injurious constituents because of their ready alteration on exposure to weathering, which causes disintegration and unsightly discoloration from iron oxide stain, as well as liberating H_2SO_4, a highly corrosive acid.

Pyrite

General properties. — Pyrite (FeS_2) crystallizes in the isometric system, the common forms being the cube and pyritohedron (Figs. 24 and 25). It occurs in rocks as crystals and in shapeless grains and masses. It has no cleavage. Hardness 6–6.5; specific gravity 4.95–5.10. Color brass-yellow, becoming darker on tarnishing when exposed to weather. Luster metallic. Streak greenish black. Opaque.

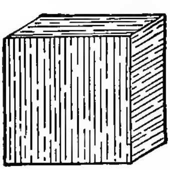

FIG. 24.

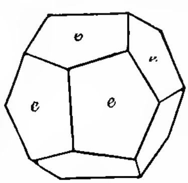

FIG. 25.

Alteration. — Pyrite alters readily on exposure to hydrous iron oxide, probably limonite chiefly. Hence rocks containing much pyrite are not suited for structural or ornamental purposes, because of its ready oxidation which serves to disintegrate and stain the rock.

Occurrence. — Pyrite is the commonest one of the sulphide minerals, and it occurs in igneous, metamorphic, and sedimentary rocks, as well as in many kinds of ore deposits. Its principal use is in the manufacture of sulphuric acid.

Chalcopyrite

General properties. — Chalcopyrite ($CuFeS_2$) is the principal ore mineral of copper. Crystals are sometimes observed, but as an ore mineral it usually occurs in irregular grains and masses. Color deep brass yellow, but tarnishes on exposure to weather. Luster metallic; streak greenish black. Hardness 3.5; specific gravity 4.25. Opaque.

Occurrence. — Chalcopyrite occurs widely distributed in many kinds of ore deposits in which it is associated with other sulphides.

Other copper sulphides. — There are several other copper sulphides which are important ore minerals of the metal. The most important one is *chalcocite* (Cu_2S), but others are *bornite* (Cu_5FeS_4), *enargite* (Cu_3AsS_4), *covellite* (CuS), and *tetrahedrite* ($Cu_8Sb_2S_7$). In many deposits the ore minerals are admixed with such quantity of other minerals that the ore as mined may not carry more than 2 or 3 per cent of copper, when it is put through a process of concentration before being sent to the smelter.

Galena

General properties. — Galena (PbS) frequently contains enough silver to make it an important silver ore, when it is called *argentiferous* galena. The cube is the common crystal form. It also occurs in cleavable, coarse to fine-granular masses. It has perfect cubic cleavage, and the color and streak are lead gray. Luster metallic. Opaque. Hardness 2.5–2.75; specific gravity 7.5. Galena may alter by oxidation into the sulphate (*anglesite*) or the carbonate (*cerussite*).

Occurrence. — Galena is the most important ore mineral of lead and has a variety of occurrences in ore deposits in which it is associated with other sulphide minerals.

Sphalerite

General properties. — Sphalerite (ZnS), known also as blende, crystallizes in the isometric system, but as an ore mineral it is usually found in cleavable, coarse to fine granular masses. It has dodecahedral cleavage, making angles of 60° and 90°. Color variable, but commonly yellow, brown, or black. Luster usually resinous. Opaque. Hardness 3.5–4; specific gravity 4.0.

Occurrence. — Sphalerite is a common mineral and is the chief ore mineral of zinc, the Joplin district, Missouri, being the most important locality in the United States.

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CHAPTER II

ROCKS AND THEIR RELATIONS TO ENGINEERING WORK

Introduction. — Knowledge of the more important and commonly occurring kinds of rocks, their mineral composition and general properties, textures and structures, mode of occurrence and formation, is of fundamental importance to the engineer for the following reasons: (1) Rocks differ greatly in their value for building purposes and road making; (2) they vary markedly in their weathering qualities — resistance to atmospheric agents; (3) they vary in hardness, which materially affects the rate of drilling them and necessarily the cost; (4) they differ widely in structure, an important factor to be considered in tunneling, quarrying operations, stability of rock cuts, dam foundations, reservoir sites, etc.

Definition of a rock. — A rock in the geological sense is the material that forms an integral part of the earth's crust. (Compare definition of a mineral on page 2.) It includes loose incoherent masses, such as a bed of sand, gravel, clay, or volcanic ash, as well as the fresh and solid masses of granite, sandstone, limestone, etc. Most rocks are aggregates of one or more minerals, but some are composed entirely of natural glass, or of a mixture of glass and minerals. Some may be composed of a mixture of organic compounds, or of a mixture of minerals and organic material. A rock may be *simple* if composed of a single mineral, such as marble made up of calcite, or quartzite made up of quartz; or *compound* if composed of several minerals, such as granite which is composed of a mixture of feldspar, quartz, and frequently mica.

Stone is an engineering or architectural term and has no significance except as indicating a certain kind of structural material.

Many common rock names are loosely used, which often leads to trouble. In letting contracts for quarrying, tunneling, etc., the contractor may often base his estimates on the nature of the rock to be removed, and neglect on the part of either party to properly designate the kind of material to be taken out has frequently led to serious results.

In the study of rocks the following essential features should be considered before describing the individual types: (1) Mode of occurrence

or geological relations; (2) composition or character of the component minerals; (3) texture or manner of aggregation of the component minerals; and (4) structure or mode of arrangement. These subjects are treated in the following pages of this chapter, and in each case the practical bearing is pointed out so far as is possible.

Varieties of rocks. — Many principles have been made the bases of various schemes for grouping or classifying rocks, a discussion of which is beyond the scope of this book. Based on the principle of genesis rocks may be grouped into three large classes, now recognized quite generally by all geologists. These are: (I) *Igneous rocks*, those which have solidified from molten material. (II) *Sedimentary rocks* (also called *stratified* rocks), those which have been laid down chiefly under water (*aqueous*) by mechanical, chemical, or organic agents; and a smaller group of wind-formed rocks (*æolian*). (III) *Metamorphic rocks*, those which have been formed from original igneous or sedimentary rocks by alteration, through the action of subsequent processes which have resulted in partly or wholly obscuring the characters of the original rock.

IGNEOUS ROCKS

Occurrence and Origin

When fresh and unaltered, igneous rocks frequently possess certain characters by which they may be distinguished from sedimentary and metamorphic ones.

Evidence gained by careful study in the field as to the mode of occurrence, whether formed as dikes, etc., will frequently determine the igneous origin of a rock. Again, mineral composition serves as an important aid. If composed wholly or partly of glass, the rock is certainly of igneous origin; or, if made up of mineral aggregates, the presence of certain minerals is strong evidence of igneous origin. Finally, texture and structure oftentimes furnish an important means of identification. At times the igneous rock may, by its temperature or in other ways, have altered the surrounding rock near the contact in a characteristic manner. Fossils are not found in igneous rocks, except rarely in tuffs.

Mode of Occurrence

Igneous rocks, formed by the consolidation of molten material, have their source within the earth at some unknown depth beneath the surface. Under proper conditions this molten material is forced upward at times for one cause or another towards the surface of the

earth, invading other kinds of rock. It may be arrested at some depth below the surface where it is cooled and solidified under the influence of the surrounding rocks, or it may reach the surface and be poured out upon it, solidifying to form hard rock.

This conception leads to a two-fold division of igneous rocks. (1) Those that have solidified at considerable depths beneath the surface, designated *intrusive* or *plutonic;* and (2) those that have solidified at or on the surface, designated *extrusive* or *volcanic.* Each of these may be further subdivided.

Intrusive or Plutonic Rocks

Forms of intrusive rocks. — The principal modes of occurrence of intrusive igneous rocks usually recognized are *dikes, sheets* or *sills, laccoliths, necks, stocks,* and *batholiths.*

Dikes. — Dikes result from the filling of fissures in other rocks (Fig. 26) by molten material from below, and there solidified. They

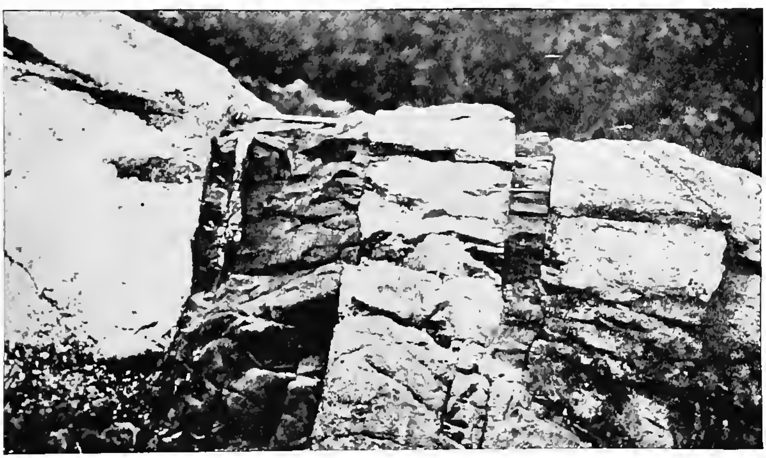

Fig. 26. — Parallel dikes of diabase cutting pegmatite dike, near Pourpour, Quebec. (H. S. Spence, photo.)

are the simplest form of intrusion, and have great length as compared with thickness; hence, they are elongated and relatively narrow bodies, which may range from a fraction of an inch in width and a few yards in length to a hundred feet and more across and miles in length. They may vary from vertical to horizontal, but the most frequent attitude is that of vertical or nearly so.

Dikes may frequently be observed extending outward from larger masses of intruded rock (Fig. 32), but in many cases such relationship

is not visible. They may continue along remarkably straight lines or follow irregular or sinuous courses (Fig. 27). A large dike may

FIG. 27.—Irregular granite dikes cutting gneiss, Moose Mountain, Ont. (H. Ries, photo.)

divide into two or more smaller ones which continue usually in the same general direction, and stringers are common. The igneous rock

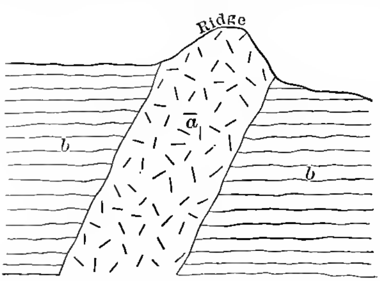

FIG. 28.—Section through dike more resistant to weathering than the inclosing rock, marking the position of a ridge. (*a*) dike; (*b*) inclosing rock.

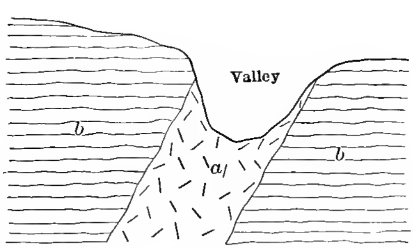

FIG. 29.—Section through dike less resistant to weathering than the inclosing rock, marking the position of a valley. (*a*) dike; (*b*) wallrock.

composing the dike may be acidic or basic in character. Large dikes usually show finer-grained texture at the margins than in the centers, while narrow ones are apt to be fine-grained throughout. Also large

dikes may sometimes show alteration of the inclosing rocks along the contacts.

Subsequent erosion and weathering of a dike may or may not result in topographic expression (Figs. 28 and 29). Usually if the dike rock is more resistant to weathering and erosion than the inclosing rocks, the position of the dike will be marked by a ridge (Fig. 28). Sometimes the opposite effect is shown and a valley-like depression results (Fig. 29). Again, it frequently happens that no topographic expression is shown. In the crystalline province of the eastern United States, frequently the only surface indication of a dike is a line of large and small boulders of the original dike rock scattered loose over the surface and partly buried in the resulting residual rock decay (clay).

Fig. 30. — Dikes of pegmatite in granite, Richmond, Va. (H. Ries, photo.) Much of rock in quarry rejected because of these dikes.

Dikes are so abundant in many areas that the engineer frequently encounters them in the field. They are often not of any value for road or building material, because of their narrow width. Their occurrence in quarries (Fig. 30) is objectionable because they spoil the stone, and sometimes crack it up badly. Abundant dikes therefore may mean much waste, unless the defective stone can be crushed for road material.

In some localities the dike rock may be weathered (but not eroded) to such an extent as to permit the access of surface water. When

such weathered dikes are encountered in underground operations, the water seeping downward along them may give trouble.[1]

Ore bodies sometimes but not always are associated with dikes, while at other times a dike of later age may cut across the ore body, a condition which sometimes has been misinterpreted, and led to the belief that the ore had given out.

Another case of error has been caused by the occurrence of somewhat broad parallel dikes, the adjoining boundaries of which were hidden by surface material, leading the engineer to suspect that the two were one large dike.

Intrusive sheets. — Intrusive sheets, known also as *sills*, are solidified bodies of molten material intruded between the stratification or foliation planes of sedimentary and metamorphic rocks, and hence they assume a somewhat bedded aspect (Fig. 31). They are characterized by relatively great lateral extent as compared with their thickness. Probably the basic and intermediate igneous rocks, such as andesites and basalts, assume the form of intrusive sheets more frequently than the acidic rocks.

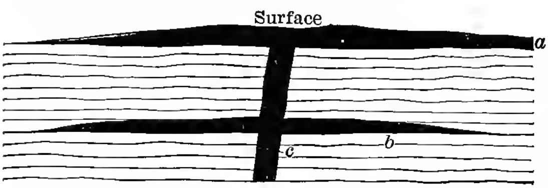

FIG. 31. — Section through (*a*), extrusive and (*b*) intrusive sheets, and (*c*) conduit.

Sheets may range from a foot to several hundred feet or more in thickness, and may cover an area many miles in extent. The Palisades of the Hudson are formed by a sheet of unusual thickness; its outcrop is 70 miles long from north to south, and its thickness varies from 300 to 850 feet. Sheets sometimes break across the strata and are continued at a new horizon. Frequently thick sheets or sills divide into several subordinate ones, each following more or less closely a bedding plane.

Sheets or sills do not always show the same mineral composition from top to bottom (see magmatic differentiation, p. 43). Where such variation exists the rock may be dark-colored or basic at the bottom and lighter-colored and siliceous at the top, affording two different types of building stone. Such difference exists in the sill of Sudbury, Ontario, with which are associated important bodies of nickel-copper ores. Sheets or sills are not of much importance as a source of build-

[1] A band of clayey rock encountered underground does not always represent decayed dike rock, but is sometimes rock which has been first crushed by movement along a fracture (faulting), and subsequently weathered by percolating water.

ing stone, but may be of value for supplies of crushed stone entirely suited for the various uses made of it.

Laccoliths. — A typical laccolith is a lenticular or dome-shaped mass of magma intruded between strata. It may be considered as a special case of an intrusive sheet in which the supply of molten material from below exceeds the rate of lateral spreading. All gradations between laccoliths and intrusive sheets may occur. A section through the typical laccolith usually shows a flat base and a convex upper surface (Fig. 32), resembling a half lens. Variations in the general structure of laccoliths are observed however, due probably, as has been suggested by some, to progressive increase of viscosity of the magma during its intrusion. In some cases the laccolith is accompanied by intrusive sheets and dikes (Fig. 32), and like the latter they may and do frequently alter by metamorphism the overlying and underlying beds. The pressure of the intruded magma forming the laccolith usually causes a lifting of

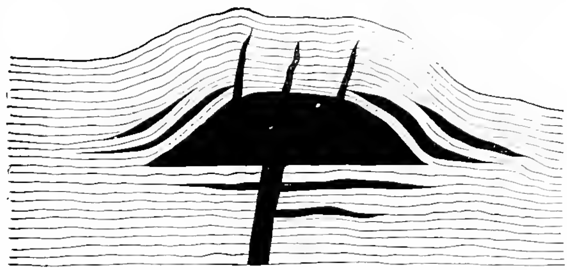

FIG. 32. — Section through laccolith showing associated sheets and dikes.

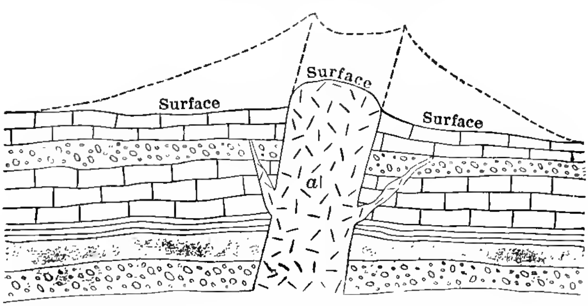

FIG. 33. — Section through volcanic neck or plug (*a*), volcanic cone shown by dotted lines, removed by erosion.

the overlying strata which may be stretched, thinned, and broken, and produces a dome-like elevation at the surface (Fig. 32).

The Henry Mountains of Utah, first described by G. K. Gilbert, form a typical representative of the laccolithic method of intrusion. Here, many stages of erosion are represented and may be observed.

Many other examples of laccoliths are known in the western United States and in Europe.

Laccoliths, like sills, may sometimes show a zoned structure, and hence the centers and margins might supply different kinds of rock.

Necks. — These are roughly cylindrical masses of igneous rock having probably great but unknown depth, which fill the vents or conduits of volcanoes. Erosion may remove practically all trace of the surrounding beds of more porous and softer volcanic ejectments, leaving the plug of resistant, consolidated igneous rock as a more or less conspicuous topographic form (Fig. 33). Volcanic necks may range up to a mile or more across, and are usually more or less circular in plan. Good examples of necks are noted in places over the western half of the United States, especially in western New Mexico.

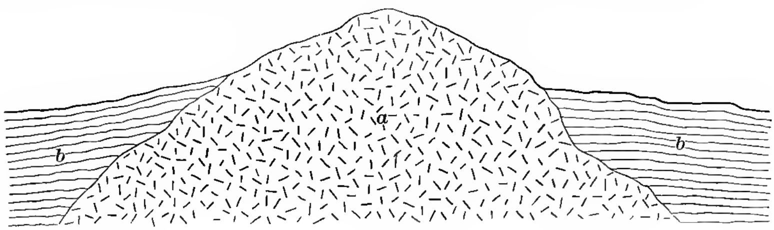

FIG. 34. — Section through stock or boss. (*a*) granite boss; (*b*) inclosing rock.

Stocks. — Stocks, known also as *bosses*, are irregular, rounded masses of igneous rock intruded and solidified at some depth below the surface, and now exposed from stripping by erosion of the thickness of overlying rocks (Figs. 34 and 36). They may range in size from a few hundred feet to several miles; and in plan they may vary from more or less circular to elliptical in outline (Fig. 35). They may cut across the inclosing rock with frequently steeply-inclined contacts which may widen with depth and along which characteristic metamorphism is often observed.

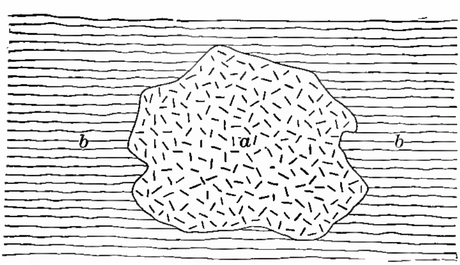

FIG. 35. — Plan of stock or boss. (*a*) granite; (*b*) inclosing rock.

Because the rock, especially granite, composing stocks or bosses is frequently of more resistant character than the surrounding rock, they become dome-like masses of steep or gentle slopes, and often-

times on account of size are conspicuous topographic forms (Fig. 36). Many stocks show an elevation of several hundred feet, and in extreme cases 700 or 800 feet and more above the surface of the surrounding rocks, such as Stone Mountain, Georgia, and the splendid granite domes of the Yosemite in California. On the other hand in regions of old land surfaces which have been continuously exposed to weathering and erosion for very long periods of time, the surface of the boss shows no topographic expression, but is more or less flat and coincident with that of the inclosing rocks.

FIG. 36. — General view of Stone Mountain, Ga., a granite boss. (After Watson, U. S. Geol. Surv., Bull. 426.)

Batholiths. — These are huge masses of plutonic rock hundreds of miles in extent which are now exposed at the surface by erosion (Fig. 37). They differ from stocks mainly in their much larger size, the small batholith and the large stock grading into each other. If they could be followed down, probably many stocks would prove to be protrusions from batholiths (Fig. 37). Batholiths form the core of many mountain ranges, like the Sierra Nevada and the Rocky Mountains, and they usually consist of some granitoid rock, of which granite is probably the commonest.

Both batholiths and stocks are important sources of granitic rock for use in structural work. The massive character of the rock, and the arrangement and spacing of the joints, make the material well adapted for the extraction of dimension blocks. In the West important ore bodies are sometimes found along the borders of such batholiths.

Extrusive or Volcanic Rocks

These may be (1) molten material poured out onto the surface from a volcanic vent or along a fissure and solidified, or (2) fragmental

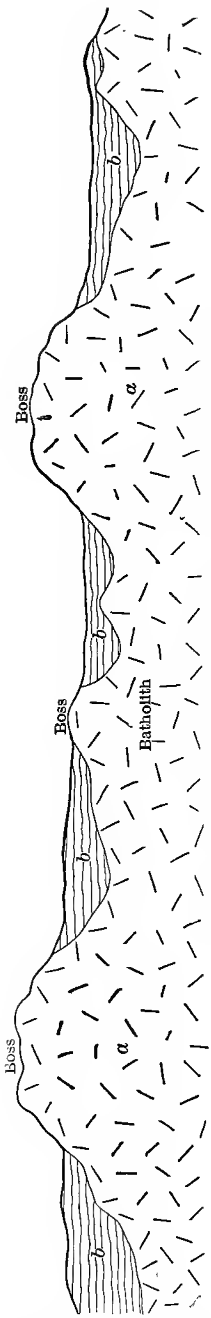

FIG. 37. — Section through a batholith. (a) granite; (b) schist.

(*pyroclastic*) material of all sizes erupted from volcanic vents. The first forms surface *lava flows* (Figs. 40 and 41) and *sheets;* the second *ash-beds* (Fig. 50) and coarser fragmental material which on consolidation yield beds of *tuffs* and volcanic *breccias.* The lava flows and fragmental materials frequently occur interstratified as shown in Fig. 38. The fragmental materials show all varieties of texture and structure, some being very fine-grained while others are very coarse, but bedding is usually pronounced.

Lava flows and sheets. — These are formed on the surface from quiet outwellings of highly molten material through (1) a volcanic vent and hence connected with volcanic eruptions, or (2) from fissures not connected with volcanic eruptions. The lava flow may be either *subaërial* or *submarine,* according to whether the eruption takes place on the land or on the sea bottom. The flows vary much in thickness, some being only a few feet while others are measured in yards.

Subaërial flows from volcanic vents may build cones having low angles of slope and of great lateral extent, according to the fluidity of the lava erupted, such as the volcanic cones of Hawaii and Iceland. Thus the more basic lavas are the more fluid. These may alternate with extrusions of fragmental material (Fig. 38), when a cone of composite character and steeper slopes is formed (Fig. 39).

In many places over the earth's surface lava flows have resulted from the quiet outpouring onto the surface through fissures, spreading in some cases hundreds of miles in extent and several thousand feet in thickness. Such *fissure-eruptions* have occurred on a gigantic scale in the Columbia River region[1] of the northwestern United States, in eastern India, in the north of the British Isles, and in historic times in Iceland.

[1] This view of the lavas of the Columbia River region has been questioned by some.

In some cases surface lava sheets have later become buried by deposition of other rocks on them through depression below sea-level. In such cases the buried sheet resembles one of intrusion, but can usually be distinguished from the latter by absence of metamorphism of the overlying beds, and the structures characteristic of the surface of lavas, such as scoriaceous, amygdaloidal, vesicular, etc.

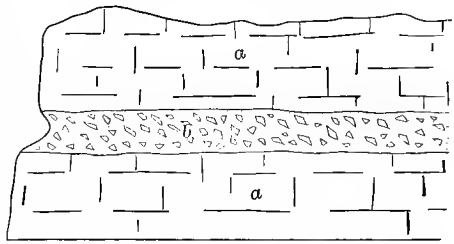

FIG. 38. — Section through a series of interbedded lava flows, and fragmental materials. (*a*) lava flows; (*b*) fragmental materials.

The fragmental (pyroclastic) materials are those which have been thrown out with great force and in enormous volume, during violent volcanic eruptions. They have settled down over the surrounding country, either on land (Fig. 50) or in water, and hence often show a stratified structure.

FIG. 39. — Volcanic cone of Colima, Mexico. Built up of ash and lava flows. Parasitic cone of 1865 on left. Ridge in foreground part of base of original cone destroyed by an explosive eruption. (H. Ries, photo.)

Engineering relationships of volcanic rocks. — In the western states and Mexico, where volcanic rocks are abundant the engineer has to deal with them. Lava flows, though often thick, are sometimes thin,

and overlie stream gravel or other deposits (Fig. 172). When testing a rock foundation for dams, reservoirs, or other structures, which are to be placed on lava flows, care should be taken that the lava cap is sufficiently thick to give a solid and impermeable base.[1]

Lava flows are not as a rule adapted to the production of large blocks. Many show columnar jointing (Figs. 41 and 49). The stone

FIG. 40. — End of an *a–a* flow of lava, Colima, Mex. (H. Ries, photo.)

at the surface of the flow may be broken up (Fig. 40), or if massive is often full of gas cavities, which may be absent deeper down (Fig. 41).

The more porous and softer volcanic rocks, like tuffs and agglomerates, can often be cut into larger blocks than the consolidated lavas. They are however usually very porous, and if possible should not be used in moist climates. Curiously enough however many of these very porous volcanic rocks are not injured by frost, probably because they do not absorb enough water to completely fill their pores.

The high porosity of tuffs and breccias may also cause trouble in dam and reservoir construction, because they permit seepage under

[1] For example see case of Zuni Dam *Eng. News* LXIV, p. 203 1909.

the walls, when the bed rock may have to be filled with grout, or sealed up in other ways. In the case of one dam foundation on the Clackamas River in Oregon, grout forced down a 50-foot pipe under 200 pounds pressure, crossed a six-foot interval in the volcanic breccia, rushed up another pipe to the surface and spurted 30 feet into the air. For similar reasons a tunnel driven through them should be lined.

FIG. 41. — Basalt lava, near Mexico City, Mex. Shows rudely columnar jointing, and gas cavities in upper portion. Quarried for paving blocks. (H. Ries, photo.)

A type of hydraulic cement, known as *puzzolan cement* is made in Europe, from a mixture of volcanic ash and lime, and a similar cement, known as *slag cement*, has been made in limited quantity in the United States.

Composition of Igneous Rocks

Under this heading is discussed (1) *chemical* and (2) *mineralogical* composition of igneous rocks. The mineral composition of igneous rocks is dependent in large measure on chemical composition of the rock magmas. When solidified under different physical conditions,

rock magmas having similar chemical composition may yield different minerals; and differences in chemical composition usually result in variations in mineral composition. Chemical composition plays a fundamental role in the classification of igneous rocks, as discussed later.

The composition of a rock magma may be changed by the solution of rocks of different composition, called *assimilation*, or by the separation of the magma into portions of different composition, known as *differentiation* (see page 43).

Chemical composition. — Rock magmas as such cannot be subjected to chemical analysis, but their cold solid products (rocks) can; and the numerous analyses made of igneous rocks from all parts of the world show them to be chiefly silicate magmas. Analyses further show that igneous rocks are composed of the acid-forming oxide, silica (SiO_2), and of the metallic oxides (bases), alumina (Al_2O_3), iron oxides (FeO and Fe_2O_3), magnesia (MgO), lime (CaO), soda (Na_2O), and potash (K_2O). Other lesser oxides, including water, are present, but usually in such small amounts that for present purposes they may be neglected. The relative proportions of these oxides in rock magmas are subject to wide variation, and they are usually combined in rocks chiefly as silicate minerals.

Igneous rocks vary greatly in chemical composition, which is used by the geologist to study their relationships, but to the engineer chemical analysis is not of much practical value.

Mineral composition. — Most igneous rocks are aggregates of minerals, a few are composed wholly of glass, and still others are made up of a mixture of minerals and glass. The important groups of these include feldspars, quartz, and the ferro-magnesian minerals, which may be tabulated under two groups as follows:

Siliceous-aluminous group (salic).	Ferromagnesian group (femic).
Alkalic feldspar	Pyroxenes
Plagioclase feldspar	Amphiboles
Nephelite	Biotite
Sodalite	Olivine
Quartz	Iron ores
Corundum	

The mineral composition affects the hardness, durability, beauty, and ability of the rock to take a polish.

Mineralogically, the acidic rocks are characterized by dominant alkalic feldspar and more or less quartz, with subordinate ferromagnesian minerals. They are rich in silica, alumina, and alkalies, but contain only small amounts of iron, lime and

magnesia, hence they are usually light in color, low in specific gravity (average about 2.6), and have a comparatively high fusion point.

The intermediate rocks contain little or no quartz, but consist chiefly of alkalic and soda-lime feldspars, with or without ferromagnesian minerals.

In the basic igneous rocks ferromagnesian minerals predominate; the dominant feldspar is a lime-soda species, quartz is absent, and olivine is frequently present. They contain less silica and alkalies than the acidic rocks, but are higher in iron, lime, and magnesia. They are more fusible, are darker in color (except in some volcanic ones), and have a relatively higher specific gravity (about 3.0 to 3.2) and as much as 3.6 in the ultrabasic rocks.

In the ultrabasic rocks, both feldspar and quartz are essentially absent, and one or more of the ferromagnesian minerals is the dominant component, either hornblende, pyroxene, olivine, or a mixture of these.

Grouping of minerals. — A convenient grouping of the rock-forming minerals which enter into the composition of igneous rocks is into (1) *essential* and (2) *accessory*. Essential minerals influence greatly the character of a rock and their presence is therefore necessary for the naming of it. For example, quartz with certain other minerals is essential to the naming of a rock granite, but if quartz be practically absent the same rock would be designated a syenite. Accessory minerals occur in small quantity and their presence or absence does not materially affect the nature of the rock. Thus, quartz and feldspar are essential minerals in granite, while zircon and apatite are accessory ones.

Another important distinction frequently made is whether the minerals are *original* or *secondary*. Original or primary minerals have formed from the solidification of the magma, while *secondary* minerals have formed from the original ones by alteration (weathering, contact or dynamic metamorphism, etc.). Thus kaolinite, sericite, talc, calcite, and epidote are secondary minerals in igneous rocks.

Essential minerals are original, but not all original minerals are essential. An essential mineral may sometimes be replaced by a secondary one, such as hornblende (uralite) which replaces pyroxene in gabbros that have been subjected to metamorphism. Some secondary minerals like kaolinite, sericite, and chlorite affect the value of rocks for road material.

Order of crystallization. — The order in which minerals crystallize from a magma is indicated by their mutual relations as seen in thin sections under the microscope, or from polished surfaces in the case of coarse-grained rocks. Thus far experience shows that minerals crystallizing from magmas do so not simultaneously but successively, with in some cases overlapping of their periods of crystallization, as shown in quartz and feldspar from the study of thin sections of granite.

The normal order generally observed in the crystallization of silicate magmas is (1) the non-siliceous minerals including the ores or oxides, (2) the ferromagnesian

minerals, (3) the soda-lime feldspars, (4) the alkalic feldspars, and (5) quartz. It will be observed from this that the order of crystallization is one of *decreasing basicity*.

Mineralizers. — Study of extrusive lavas at the time of expulsion shows the presence of considerable quantities of volatile substances, such as water vapor, carbon dioxide, fluorine, chlorine, boric acid, sulphur, etc. These dissolved vapors are known as *mineralizers*, since they exercise an important influence on mineral composition and to some extent on texture. They are present in both acidic and basic magmas. They play an important rôle in the crystallization of igneous rocks, and their action in the production of minerals from solidifying magmas may be either chemical or physical.

Texture of Igneous Rocks

By *texture* of an igneous rock is meant size, shape, and manner of aggregation of its component minerals. Some rocks are sufficiently coarse-grained in texture for the principal minerals to be readily distinguished by the unaided eye; in others the minerals are so small in size as to defy identification even with the aid of a pocket lens; and in still others no minerals have crystallized, but, instead, the magma has solidified as glass. These express the physical (rate of cooling) and not the chemical conditions under which magmas solidified, and in a general way indicate the position in the earth's crust in which they solidified. Rate of cooling, therefore, is one of the most important factors in conditioning rock texture. Other important factors that influence the development of rock texture are chemical composition, temperature, pressure, and the presence of mineralizers.

Kinds of texture. — In megascopic descriptions of igneous rocks, the principal textures recognized are *glassy*, *dense* or *felsitic*, *porphyritic*, *granitoid*, and *fragmental*.

Glassy texture. — Under conditions of quick chilling, magmas, especially the more siliceous ones, solidify as glass. Such rocks do not show definite minerals and are composed of glass, examples of which are obsidian, pitchstone, etc. Some glasses, such as *pumice*, are highly vesicular due to the escape of water vapor at high temperature through relief of pressure.

Dense or felsitic texture. — This texture (Fig. 42) is characteristic of crystalline rocks, but the individual minerals are too small in size to be distinguished by the eye. The general appearance of the rock is homogeneous and stony but not glassy. Examples, felsites and basalts.

Porphyritic texture. — Porphyritic texture is one in which relatively larger grains or crystals (phenocrysts) are set in a finer-grained groundmass (Fig. 43) that may be crystalline or glassy. The phenocrysts,

Fig. 42. — Banded felsitic texture showing flow structure.

which range from minute individuals to several inches in diameter, may consist of either light- or dark-colored minerals, or a mixture of the two. Porphyritic texture is commoner in lavas, dikes, sheets, and laccoliths than in the deeper-seated rocks, but is often seen in

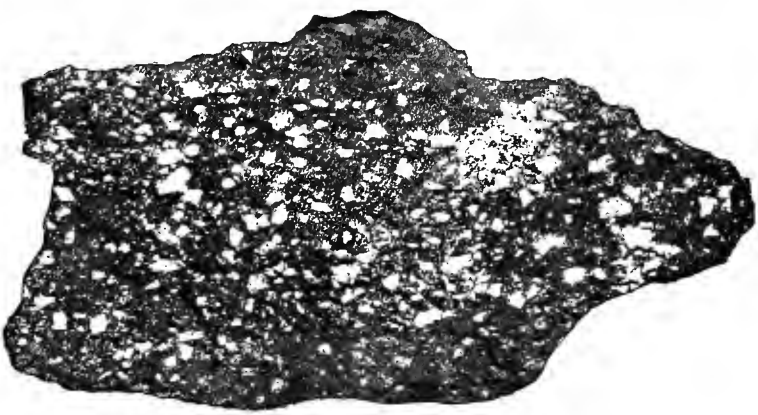

Fig. 43. — Trachyte, showing porphyritic texture.

granites. The groundmass of porphyritic rocks often weathers more rapidly than the phenocrysts.

Granitoid texture. — Igneous rocks composed of recognizable minerals of approximately the same size possess granitoid or even-granular

texture. The individual minerals seldom exhibit definite crystal boundaries. Example, normal granite. Based on size of minerals, we may recognize: (1) *Fine-grained* rocks, average size of particles less than 1 millimeter; (2) *medium-grained*, between 1 and 5 millimeters; and (3) *coarse-grained*, greater than 5 millimeters.

Other things being equal, fine-grained granitoid rocks are more durable than coarse-grained ones. They also lend themselves better to carved work.

Fragmental texture. — Fragmental is a textural term used in describing volcanic tuffs and breccias, which represent the consolidation of pyroclastic materials of all sizes.

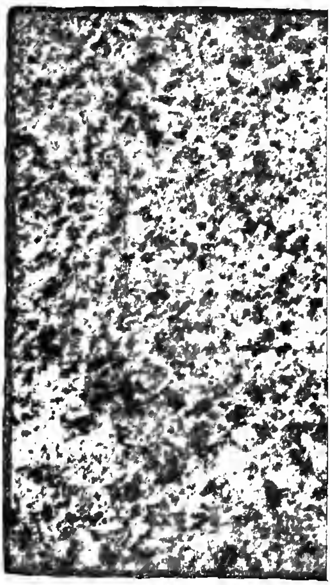

FIG. 44. — Moderately fine-grained granite, Hallowell, Me.

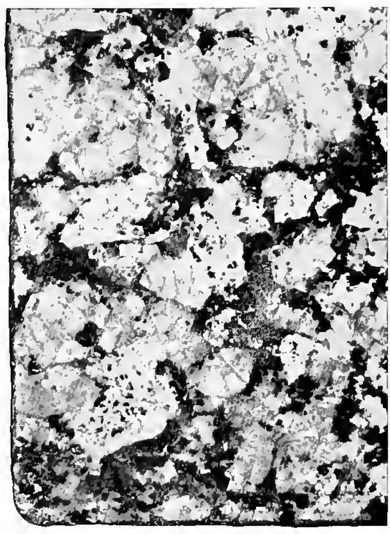

FIG. 45. — Very coarse-grained granite, St. Cloud, Minn.

Porous texture. — The volcanic glassy and felsitic rocks may vary texturally from very compact and dense to very porous, with nearly all gradations between these extremes observed. According to the abundance of cavities, caused by escaping vapors from the magma during cooling, the rock may be termed *vesicular*, *scoriaceous*, or *pumiceous*.

When these cavities have been filled with minerals deposited from solution, the rock is described as having *amygdaloidal texture*, and the minerals filling them are termed *amygdules*, because of their resem-

blance to almond-shaped forms. Amygdaloidal texture is especially common in surface lava flows of basalts. Similar cavities developed in some granites, and into which minerals project as well-formed crystals, are called *miarolitic.*

Differentiation of Rock Magmas

There is strong geologic evidence for the belief that under certain conditions, magmas separate into submagmas of unlike composition, and each different in composition from that of the original magma. This process of a parent magma separating into submagmas is known as *magmatic differentiation.* Differentiation of rock magmas may occur in several ways, but their discussion is beyond the scope of this book.[1] It may take place prior to intrusion or extrusion or it may go forward after the magma has reached its final resting place. The separate magmas may be characterized by differences either in mineral or in chemical composition.

Plutonic igneous masses, such as granite stocks, etc., exposed now at the surface through erosion, frequently show a somewhat zoned arrangement; an outer margin of irregular width and extent whose mineral composition is essentially different from that of the larger central mass. That is to say, a border zone consisting of a greater concentration of the more basic, and sometimes the more acidic, minerals than in the central mass. The two parts of the igneous mass usually contain the same minerals, but in different concentrations, and the passage from one to the other is frequently gradual.

The process of magmatic differentiation has been an important one in the formation of some ore bodies such as those of magnetite, ilmenite, chromite, etc.

Classification of Igneous Rocks

Igneous rocks possess certain features by which the many different varieties recognized may be distinguished from each other, such as mode of occurrence, texture, mineral composition, chemical composition, etc. It often happens that the identification of the exact variety of igneous rock is not possible by megascopic methods, but must be determined by microscopical and chemical study. The engineer, however, must rely on megascopic characters of igneous rocks in classifying them, using a scheme that is not only practical, but one that is based on the principal rock characters, such as texture and mineral composition.

Volcanic rocks may be glassy, stony, cellular, or porphyritic in texture, while the plutonic rocks are generally massive and crystalline granular, with porphyritic texture by no means uncommon. A rock, therefore, may have a uniform mineral composition, but vary in tex-

[1] Those interested in the subject of differentiation of rock magmas, see the following references: J. P. Iddings, Igneous Rocks, Vol. I, 464 pp., 1909 (John Wiley & Sons); R. A. Daly, Igneous Rocks and Their Origin, 563 pp., 1914 (McGraw-Hill Book Company); A. Harker, The Natural History of Igneous Rocks, 384 pp., 1909 (The Macmillan Co.).

ture, depending upon the conditions under which it solidified. On the other hand, plutonic rocks may possess similar texture, but differ in mineral composition. These differences, mineralogical and textural, lead to the development of different varieties of igneous rocks.

The following table, taken from Pirsson, expresses simply the mineralogical and textural characters of the more common kinds of igneous rocks, and is admirably adapted to the needs of the engineer.

MEGASCOPIC CLASSIFICATION OF IGNEOUS ROCKS

(A) Grained, constituent grains recognizable. Mostly intrusive.

	(*a*) Feldspathic rocks, usually light in color.		(*b*) Ferromagnesian rocks, generally dark to black.	
	With quartz.	Without quartz.	With subordinate feldspar.	Without feldspar.
Even-granular (non-porphyritic)	GRANITE. (*a*) Aplite.	SYENITE. (*a*) Syenite. (*b*) Nephelite syenite. (*c*) Anorthosite.	DIORITE. GABBRO. DOLERITE.	PERIDOTITE. Pyroxenite. Hornblendite.
Porphyritic.....	GRANITE-PORPHYRY.	SYENITE-PORPHYRY.	DIORITE-PORPHYRY.	

(B) Dense, constituents nearly or wholly unrecognizable. Intrusive and extrusive.

	(*a*) Light colored, usually feldspathic.	(*b*) Dark colored to black, usually ferromagnesian.
Non-porphyritic..............	FELSITE.	BASALT.
Porphyritic...................	FELSITE-PORPHYRY.	BASALT-PORPYHRY.

(C) Rocks composed wholly or in part of glass. Extrusive.

Non-porphyritic	OBSIDIAN, pitchstone, pearlite, pumice, etc.
Porphyritic......................	Vitrophyre (obsidian- and pitchstone-porphyry).

(D) Fragmental igneous material. Extrusive.

TUFFS, BRECCIAS (Volcanic ashes, etc.).

Granite. — A granular rock composed of feldspar and quartz, with usually mica (biotite or muscovite) or hornblende, rarely pyroxene, but some granites consist of feldspar and quartz alone. Accessory minerals are not abundant and are usually microscopic. Granites are sometimes named according to the predominant silicate mineral present with the quartz and feldspar, as biotite granite, etc. *Pegmatite* is a coarse-grained granite occurring in dikes or veins. *Graphic granite* is a pegmatite in which quartz and feldspar are intercrystallized so as to resemble cuneiform characters (Fig. 46).

The usual color of granite is gray, pink, or red, dependent chiefly upon the color of the feldspar and the proportion of it to dark minerals. Texture ranges from even-granular (Fig. 44) to porphyritic, and from coarse (Fig. 45) to fine. When made banded or schistose by dynamic metamorphism they pass into gneisses and schists respectively. Specific gravity ranges from 2.63 to 2.75, or 165 to 172 pounds per cubic foot. The percentage of absorption is less than one per cent, and the crushing strength ranges on the average from 15,000 to 30,000 pounds per square inch, properties which render the rock especially desirable for building purposes. Other properties which may be tested are elasticity, transverse strength, and fire resistance.

Fig. 46. — Graphic granite, showing characteristic intergrowth of quartz (dark) and feldspar (light).

Granites have a minimum of porosity and structurally are normally massive without foliation or bands. When a foliated or banded structure is developed subsequent to crystallization, the rock grades from a foliated granite into a *granite-gneiss*. Segregations (knots) and inclusions of foreign rocks may be present and detract from the commercial value of the stone.

Granites are plutonic rocks that have cooled at depth beneath the surface, forming batholiths, stocks or bosses, and dikes. They form

an important building stone, which is somewhat widely distributed in the United States (Fig. 47), but most of that which is quarried comes from the eastern United States. The producing areas are (1) a belt extending from Maine to Alabama, (2) the Minnesota-Wisconsin area, (3) Missouri-Oklahoma-Texas district, (4) Cordilleran region, and (5) the Black Hills of South Dakota. The coarser-grained and medium-grained granites are widely used for massive structural work, but other varieties, on account of fine grain, color, and ability to take a high polish, are employed for decorative, monumental, and inscriptional purposes. Pegmatite dikes serve as a source of feldspar and mica.

Syenite. — This is a granular rock composed normally of the same minerals as granite, except that it contains little or no quartz. Like granite the accessory minerals are chiefly microscopic. The more important varieties of *syenite proper* are *mica, hornblende,* and *augite* syenite.

Syenites are massive, even-granular rocks, sometimes porphyritic, having the same color as granites, and a specific gravity of 2.6 to 2.8. Like granites they may be characterized by joints, segregations (knots), and inclusions, and may show banding from metamorphism. They are not common rocks, but have equal value to granite for constructional purposes. The most important commercial area of syenite in the United States is near Little Rock, Arkansas, where the rock has been quarried for some time. Like granite, syenite forms independent masses and dikes, and is frequently associated with large bodies of granite, into which it may grade.

Diorite. — Diorites are granular rocks composed of plagioclase feldspar and hornblende or biotite, and often some augite. The dark ferromagnesian silicate equals or exceeds feldspar in amount. Quartz sometimes occurs in quantity when the rock is termed *quartz diorite. Monzonite* is an intermediate type between syenite and diorite, and *quartz monzonite* or *granodiorite* is intermediate between granite and quartz diorite.

Diorites are usually dark-colored, heavy (specific gravity 2.85–3.0), massive, fine to coarse even-granular rocks, but may be porphyritic in texture. When made schistose from dynamic metamorphism they pass into gneisses and hornblende schists. Diorites are widely distributed rocks, occurring as stocks and dikes, less often as batholiths, and are found connected with granite and gabbro into which they may grade. Diorite proper is not much used as a building stone, but the granodiorites of the Sierra Nevada Mountains in California are extensively quarried. The uses of diorite are similar to those of granite.

Fig. 47. — Map showing distribution of igneous rocks and gneisses in the United States. (After G. P. Merrill, "Stones for Building and Decoration.")

Gabbro. — A granitoid intrusive rock composed of pyroxene and plagioclase feldspar with the former usually in excess, but rocks called *anorthosites*, composed practically of all plagioclase (labradorite), are included. Olivine occurs in quantity in some gabbros which are known as *olivine* gabbro. The many varieties of gabbro known are based on microscopic distinction in mineral composition and texture. *Diabase*, an important variety, has the characteristic *ophitic* or diabasic texture (Fig. 48), and occurs commonly as dikes, but also as

FIG. 48. — Photomicrograph of a section of diabase, showing ophitic texture.

sills in the eastern Atlantic States (Palisades of Hudson River) and is used chiefly for road material and paving blocks. It is rarely employed for dimension stone, because of its great toughness, abundant and irregular jointing, as well as absence of rift and grain.

Gabbros proper are dark-colored rocks similar to diorites in texture and structure. The specific gravity will average between 2.9 and 3.2. They possess a high degree of compressive strength and low absorptiveness, and are well suited for constructional purposes, in which they have had a limited use. They are susceptible of a high degree of polish and have been used to some extent for monumental stock, but their very dark color has militated in part against extended use in this direction.

Original banded structure may be noted in some gabbros, and dynamic metamorphism may mash them into gneisses or schists. Segregations of magnetite and ilmenite, and of pyrrhotite, are common in many gabbros, especially those of Wyoming, Minnesota, New York, and Canada, and of Norway and Sweden in Europe.

Gabbros are fairly common rocks and have rather wide distribution as batholiths, stocks or bosses, and dikes. They occur in abundance in the Adirondack Mountains of New York State, to a less extent in the vicinity of Baltimore, Maryland, and that around Duluth, Minnesota, has been used for building purposes. Gabbro is not much used for structural work, because of lack of regular jointing, absence of pronounced rift and grain, dark color, and often great toughness. Occasionally, however, it is selected for monumental work, because of its fine color and ability to take a good polish.

Peridotite. — Peridotites are ultrabasic intrusive rocks consisting chiefly of olivine, with usually more or less pyroxene, sometimes hornblende, and with little or no feldspar. *Dunite*, composed chiefly of olivine, is an important variety. Accessory minerals usually present are chromite, ilmenite, and garnet. The commercial source of chromite is from concentrations in magmatic segregation deposits in peridotites and their alteration product serpentine.

Peridotites are usually very dark, massive-granular rocks having a specific gravity of 3.0 to 3.3. Under atmospheric conditions peridotites are very susceptible to rapid alteration, the chief product being serpentine, with talc not uncommon. They occur chiefly as dikes, although sheets and stocks are known, and they are sometimes associated with gabbro, into which they may grade.

Volcanic or Dense Igneous Rocks

Introduction. — In this group are included those igneous rocks that have formed on or near the surface. Because of rapid cooling the minerals are so small in size that with the exception of the phenocrysts in some porphyritic lavas, they cannot be distinguished by the naked eye. Hence they are usually referred to as dense igneous rocks in contradistinction to the grained igneous rocks that have formed at depth beneath the surface, and whose principal minerals are usually large enough to be identified megascopically, because of slower cooling. The two groups of rocks, however, grade into each other, and no sharp line of demarcation can be drawn between them.

The volcanic rocks may be classified in the same manner as the plutonic igneous rocks, and for every type of the latter there is a volcanic equivalent. For such refined classification of the volcanic

rocks we must rely on the methods of microscopic study of thin rock sections. On this basis we may make the following divisions of the volcanic rocks corresponding to the plutonic equivalents described in the following pages and shown in tabular form below.

Volcanic	Plutonic
Rhyolite	Granite
Trachyte	Syenite
Phonolite	Nephelite-syenite
Dacite (Quartz andesite)	Quartz diorite
Andesite	Diorite
Augite (Andesite)	Gabbro
Basalt	Olivine gabbro
Augitite	Pyroxenite
Limburgite	Peridotite

For megascopic purposes this grouping of volcanic rocks cannot be followed, since the principal minerals are indistinguishable by the naked eye. By adopting color as the basis of classification, which expresses in a general way the mineral composition of the rocks as to whether light- or dark-colored minerals predominate, we may group the volcanic rocks into two principal divisions, namely, (1) *felsites* and (2) *basalts*. On the color basis, felsites comprise the light-colored (acidic) volcanic rocks, while the basalts include the dark-colored (basic) ones.

Felsite.—This includes dominantly feldspathic varieties of fine-grained volcanic rocks, with or without quartz, which are light in color and weight (specific gravity about 2.6) and comprise the microscopic types rhyolite, trachyte, and phonolite. They sometimes show porphyritic texture, when they may be designated *felsite porphyry*. Vesicular or cellular structure is less common than in basalts, but they frequently show flow structure. Since the felsites are very fine granular such division as may be made of them megascopically must be based on color and texture.

The felsites occur chiefly as dikes and lava flows or sheets, and are found in many localities in the eastern United States, but are especially abundant as lava flows and sheets in the West. Felsites are little used for building purposes in the United States, but they are widely employed in Mexico. They do not possess as a rule as great strength as the plutonic igneous rocks, but nevertheless they can be often used for ordinary constructional work. Few of them are sufficiently dense to take a polish, and the more porous ones should not be used in moist locations.

Basalt. — Basalts include very dark-colored igneous rocks corresponding to felsites in texture. They include the microscopic varieties andesite, basalt, augitite, and limburgite. Mineralogically they agree with the diorites and gabbros, and are gray black to black in color. Cellular and amygdaloidal structures are common, and while porphyritic texture is sometimes observed it is less frequent than in felsites. Pyroxene, olivine, and feldspar may occur as phenocrysts, when the rock is called *basalt porphyry*, which bears the same relation to basalt that felsite porphyry does to felsite.

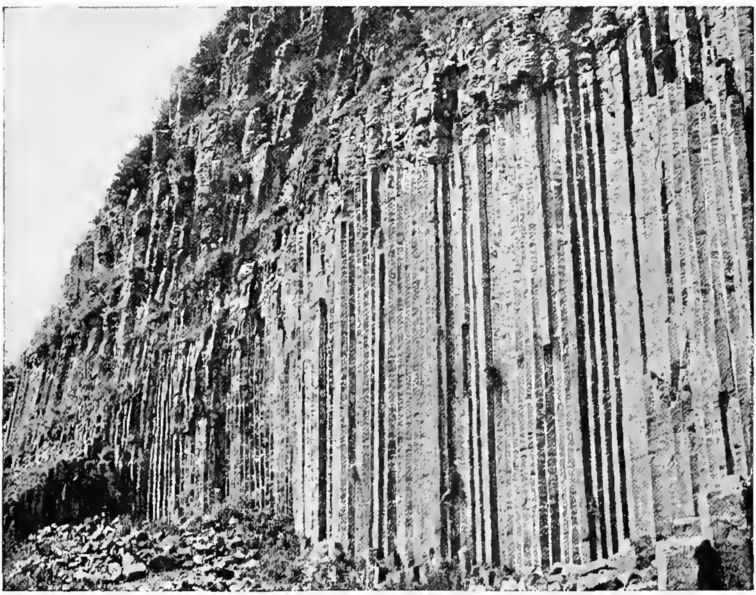

Fig. 49. — Columnar jointing in basalt, Le Puy, France.

The basalts megascopically are recognized by their dark color and high specific gravity 2.9 to 3.1. Columnar jointing is common (Fig. 49), one of the best examples being that of the Giants' Causeway on the north coast of Ireland.

Basalts are widespread in occurrence, chiefly as lava flows or sheets, and dikes. They are abundantly developed both in the eastern and western United States, the most extensive area being that of the Snake River region of Idaho, Oregon, and Washington, the dark lava beds having an areal extent of many thousand square miles and hundreds of feet in thickness.

The porous, cellular varieties of basalt are not as a rule desirable for use as constructional material, but there seems no reason why the

dense compact varieties should not be used in those regions where they occur, although their toughness and abundant jointing make the extraction of dimension blocks difficult. Color and lack of susceptibility to good polish preclude basalt from being used for interior decoration. Its principal uses at present are for macadamizing and paving roads and streets.

Glassy Igneous Rocks

Glassy igneous rocks are composed essentially or entirely of glass, and they represent, with only rare exceptions, molten lavas poured out onto the surface which have undergone quick solidification, aided probably by the rapid escape of mineralizers. Any magma under proper conditions of rapid chilling may solidify as glass, but the acidic ones corresponding to granite in composition are the most common.

Some glassy rocks may show distinct crystals (phenocrysts), and are known as *glass porphyry* or *vitrophyre*, but porphyritic texture is more often not developed. We may recognize the following principal varieties of glassy rocks, based on luster and structure: *Obsidian*, a homogeneous glass, of bright vitreous luster, jet black to red in color, and having conchoidal fracture; *pitchstone*, a homogeneous glass of dull or resinous luster, black to red, brown, and green in color, and containing from 5 to 10 per cent of water; *perlite*, a glass broken by concentric cracks on cooling, and made up of small spheroidal masses, usually of gray color, rarely red; *pumice*, an excessively porous or cellular glass, due to the escape of water vapor at high temperature through relief of pressure, and usually white or gray in color, though darker shades are sometimes shown.

The glassy rocks vary from dense and compact homogeneous rocks, having conchoidal fracture, to those that are highly porous, and may show characteristic flow structure (Fig. 42). The usual range in specific gravity is from 2.34 to 2.7. The glassy rocks sometimes occur as independent sheets and dikes, but usually they form the surface of lava flows and at times the marginal portions of dikes. They are especially abundant in the West, but are also found in the eastern United States. Obsidian Cliff in the Yellowstone National Park is a noted locality. Volcanic glasses have not been quarried for commercial purposes, but some of them could be used to advantage as interior decorative stone, since some are quite ornamental and are susceptible of a high polish.

Porphyritic Igneous Rocks (Porphyries)

The term porphyry includes all igneous rocks, regardless of mineral composition, that show porphyritic texture. Megascopically the porphyries may be subdivided into (1) those porphyritic rocks whose principal groundmass minerals may be distinguished by the naked

eye; and (2) those porphyritic rocks whose groundmass is either felsitic or glassy in texture, and only the phenocrysts may be identified by the unaided eye.

The first group will include the granitoid rocks having porphyritic texture, such as *porphyritic granite, porphyritic syenite,* etc., with feldspar the most frequent mineral formed as phenocrysts. The second group includes all felsitic and glassy igneous rocks having porphyritic texture, such as *felsite porphyry, basalt porphyry,* etc. The phenocrysts may consist of either light-colored (quartz and feldspar) or dark-colored (hornblende, pyroxene, biotite, or olivine) minerals.

In composition, specific gravity, alteration, etc., the porphyries are similar to their corresponding grained types, and from the standpoint of durability they may be utilized for the same purposes. They have wide distribution, and show a variety of color. Many of our important ore deposits of the West are associated with porphyries, where the word porphyry is used for almost every igneous rock occurring in sheets or dikes in connection with ore deposits (Kemp).

In many porphyries, the phenocrysts contrast strongly in color with that of the groundmass, and exhibit a beautiful effect on polished surfaces. They are hard and durable, usually without rift or grain, and often of beautiful color, but have been used to a very limited extent as decorative stone in the United States.

Volcanic Fragmental (Pyroclastic) Rocks

Under pyroclastic rocks are included all fragmental materials erupted by volcanoes, regardless of size and shape. Masses of rock weighing tons are sometimes thrown out, and from this size the material grades down to that of dust-like particles.

The different kinds of volcanic fragmental materials recognized are: (1) *Volcanic blocks,* the large irregular-shaped masses, angular to somewhat rounded, and measuring several feet and more in size; (2) *bombs,* round or elliptical-shaped masses of lava, ranging from a few inches up to a foot and more in diameter; (3) *lapilli,* fragments of lava of indefinite shape, ranging in size from a pea to that of a walnut; and (4) *volcanic ash* (Fig. 50), the finer particles of lava ejected, including all sizes below that of a pea.

The larger fragments accumulate near the vent or opening, while the finer material may travel some distance before falling to the surface. They may cover extensive areas and accumulate to considerable depths, and are sometimes interbedded with lava flows as shown in Fig. 38. Consolidation of the fragmental material into more or less firm rock may take place either on land or under water; in either

case the rock usually shows stratification. The finer volcanic materials after consolidation yield *volcanic tuffs;* the larger and coarser materials give *volcanic breccias.* Other names, such as *volcanic agglomerate* and *volcanic conglomerate,* have been applied to the consolidated coarse material, according to size and shape of the fragments.

The volcanic tuffs and breccias may receive different names, according to the nature of fragments composing them, such as *rhyolite-tuffs*, etc.

Fig. 50. — Volcanic ash deposits on lower slopes of extinct volcano of Toluca in Mexico. (H. Ries, photo.) Note how the ash has been gullied by rain.

The volcanic fragmental rocks may show a variety of color, and the more recent ones are soft and porous, and are capable of absorbing large quantities of water. The older ones are often compact and hard and their fragmental character may not be evident to the naked eye. They may be moderately strong, but are usually light in weight.

Volcanic tuffs have wide distribution in the West, and have more restricted occurrence in the East. They have been employed only to a limited extent for building purposes in this country, but have a more extended use in Mexico and locally in several of the European countries. They are usually soft and easy to work, but owing to their porous nature they may be used to best advantage only in dry climates. As a rule, they will not polish because of their textures.

SEDIMENTARY ROCKS

Introduction. — Sedimentary rocks, known also as *stratified rocks,* are of secondary origin, since they have been formed chiefly from pre-

existent ones. A few have been formed from the remains of plants and animals. The source of the material of most sedimentary rocks may have been derived from pre-existing igneous, metamorphic, or stratified rocks. Indeed, the earliest sediments are regarded by most geologists as having been derived from already existing igneous rocks.

The materials composing sedimentary rocks have been laid down under water or on land, and have been derived by disintegration and decomposition of pre-existing rocks, and of plants and animals, as discussed in Chapter IV. This material has been moved from its original position as (1) partly débris in the form of solid particles of different sizes and shapes; and (2) partly dissolved salts in solution. The principal agents involved in shifting the position of this material are: (1) Moving water, forming *aqueous sediments*, which comprise the vast majority of sedimentary rocks; (2) mechanical action of wind forming *æolian sediments*, which are of less importance; and (3) ice, chiefly glacial, forming in this case *glacial sediments*.

According to the agents involved in the deposition of sedimentary rocks we may have (1) *mechanically-formed sediments;* (2) *chemically-formed sediments;* and (3) *organically-formed sediments.*

General Properties of Sedimentary Rocks

Variation in size of material. — The products of rock decay vary greatly in size, but when subjected to the action of running water they are sorted and graded into particles of approximately equal size, in accordance with the strength of current, as explained in Chapter V. Grouped then according to size, beginning with the coarsest, the names for this material are: (1) *Boulders* and *cobbles*, the coarsest material, ranging down to 3 or 4 inches in diameter; (2) *gravel*, including all material below cobble size down to 1 millimeter ($\frac{1}{25}$ in.) in diameter; (3) *sand*, ranging from 1 to 0.05 millimeter ($\frac{1}{25}$ to $\frac{1}{500}$ in.) in diameter; and (4) *clay* and *silt*, ranging from 0.05 to 0.0001 millimeter ($\frac{1}{500}$ in. to $\frac{1}{250000}$ in.) in diameter. Gradation of these into each other is very common.

Texture of sedimentary rocks. — Texture relates to size and shape of the individual grains composing the rocks. The size of the grains varies from boulders and gravel (Fig. 56) through sand to silt or clay. The shape of the grains depends chiefly upon the amount of wear they have suffered in transit if moved by running water; ranging from smooth and well rounded, through subangular, to angular. The rounded water-worn coarse material when consolidated yields *conglomerates* (Figs. 52, 56), but when angular and consolidated produces *breccias* (Figs. 51, 54). The texture of a sedimentary rock affects,

to some extent, its value as a building stone. Other things being equal, fine-grained ones usually carve and split better, as well as being often more durable.

Consolidation of sediments into solid rock. — The loose materials described above may be cemented into solid rock by the deposition of mineral matter from percolating waters, converting them from loose

FIG. 51. — Sketch showing structure of a breccia.

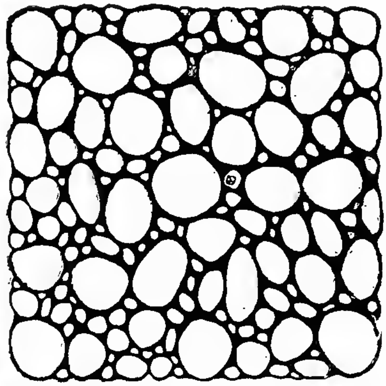

FIG. 52. — Sketch showing structure of a conglomerate.

masses into solid firm rock. The common cementing substances deposited from solution are silica, calcium carbonate, and iron oxide, but the finer clay-like substances mechanically deposited with the coarser material may also act as the cement. The finer sediments like clay, mud, etc., may be converted into solid rocks by pressure, but whether cementation is by deposition of material from solution or by pressure, the time element is an important factor, since transformation from loose material into solid rock is usually a slow process.

In some sandstones, the cement is composed to a large extent of secondary minerals, as some of the feldspathic sandstones which were examined for use in the construction of the Ashokan dam in the Catskill Mountains, their exceptional strength being due to modifications of texture that resulted from the alteration and reconstruction of the mineral constituents.[1]

Quantity of cement. — All gradations may exist between hard, firm, and compact rocks to more or less loose and friable ones. A rock may be composed entirely of hard grains, such as quartz, and yet be bound together by so little cement that the rock as a whole is soft and porous. On the other hand, a rock although composed of soft mineral grains

[1] Berkey, Sch. of M. Quart., XXIX, p. 140, 1908.

like calcite may be so firmly held by the cement as to form a hard, dense mass. We can see from this that the strength of a sedimentary rock must depend mainly on the tightness with which the grains are bound together, for the mineral particles do not interlock as in igneous rocks. The quantity as well as kind of cement may therefore influence the stone's porosity, hardness, crushing strength, and resistance to abrasion and frost.

Color of cement. — Iron oxide cement is some shade of yellow, red, or brown; silica and calcium carbonate if free from impurities are white; and clay, if present in appreciable amount, may impart a grayish color. Silicates, sometimes of secondary character, may give the stone a bluish or greenish tint. Two kinds of cement may be present in the same rock.

The color of a sedimentary rock, as influenced by the interstitial coloring material, is a matter of some importance if the stone is to be used for decorative purposes.

Durability of cement. — Silica normally forms the most durable kind of cement in rocks exposed to the chemical action of the atmosphere; iron oxide is next, and calcium carbonate the least durable. Clay, if present in small amounts and evenly distributed, probably does no harm. It facilitates the working qualities of the stone, but if very abundant it tends to attract moisture to the rock which lowers its frost resistance.

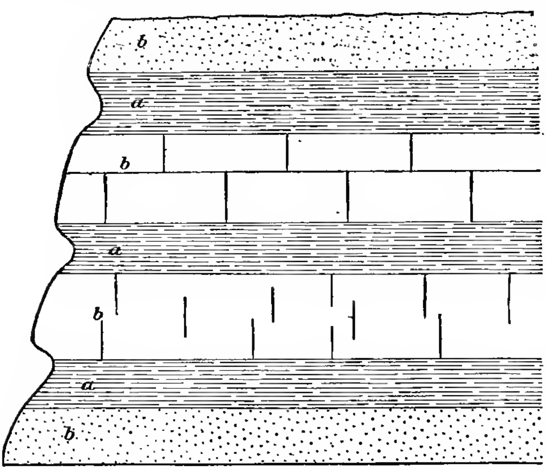

FIG. 53. — Section showing stratification and lamination; (*a*) laminated beds.

Structure of sedimentary rocks. — Most sedimentary rocks are characterized by original bedded structure (Fig. 57), known as *bedding* or *stratification* (Fig. 53) (called *lamination* in the finer-grained sediments). The lines of parting between individual beds or strata are called *bedding planes.* Such structure in sedimentary rocks results from the sorting action of water and wind; hence, the materials are disposed in sheet-like form. The sediment is deposited in layers,

usually horizontally or nearly so, and in superposition. The process of sedimentation may be more or less rapid, or gradual, and protracted. The layers may vary as to kind of material, color, texture, and thickness. Variation in thickness of individual layers may range from a very small fraction of an inch up to 100 feet and more, hence we distinguish *beds* or *layers*, and *laminæ* (Fig. 53). The terms *bed* and *layer* as generally used are synonymous and refer to the thicker divisions, while *laminæ* are applied to the thinner ones. *Stratum* is generally applied to a single bed or layer of rock, while a group of beds deposited in sequence one above another and during the same period of geologic time is known as a *formation*. The thickness of the individual layers affects the value of the rock for building stone, as well as its stability and strength in tunnel construction, etc.

Stratification. — The stratification planes present in all quarries of sedimentary rocks exert an influence similar to joints. They facilitate the extraction of the stone, but when too closely spaced, they may make the stone so slabby that it is of no use except for flagging purposes. They may also afford more ready channels of access for surface waters and thus cause the rock to weather.

If the beds dip at a high angle, the water naturally runs in more readily along the bedding planes, and not only discolors or decays the rock along them, but keeps the quarry wet and involves extra cost of pumping, unless the quarry be self-draining.

Composition of sedimentary rocks. — Sedimentary rocks are in general more simple in mineral composition than most of the igneous ones. Fewer minerals, of less complex chemical composition, and as a rule of more stable character, make up the principal components of sedimentary rocks. This follows naturally for the reason that the sediments are composed chiefly of minerals derived by weathering from preëxisting rocks, hence, under surface conditions, the minerals are less complex in composition and more stable in character. The most common minerals composing sedimentary rocks are quartz, kaolinite, feldspar, mica, and the iron oxides, together with those precipitated from solution, such as the carbonates (calcite, dolomite, and siderite), and the sulphates (gypsum and anhydrite), as well as a few less commonly-occurring ones.

The chemical composition of a sedimentary rock is of little practical importance except in the case of (1) limestone and gypsum, to indicate their value as cementing materials; (2) coals, to indicate their rank and the presence and character of impurities; (3) phosphates, to show their phosphoric acid content; and (4) clay used in Portland cement.

Classification of Sedimentary Rocks

The classification of sedimentary rocks best suited to the needs of the engineer, and the one adopted in this book, is based on (1) mode of formation and (2) composition and physical characters. The one tabulated below is adopted from Pirsson.[1] It follows:

I. Sediments of mechanical origin.
  1. Water deposits.
    a. Conglomerates and breccias.
    b. Sandstones.
    c. Shales and clays.
  2. Wind deposits.
    a. Loess.
    b. Sand dunes.

II. Sediments of chemical origin formed from solution.
  1. Concentration.
    a. Sulphates: Gypsum and anhydrite.
    b. Chlorides: Halite (rock salt).
    c. Silica: Flint, geyserite, etc.
    d. Carbonates: Limestone, travertine, etc.
    e. Ferruginous rocks: Iron ores.
  2. Organic, formed through the agency of animals and plants.
    a. Carbonates: Limestone of several kinds.
    b. Silica: Flint, diatomaceous earth, etc.
    c. Phosphate: Phosphate rock.
    d. Carbon: Coal, etc.
    e. Hydrocarbon-bearing sediments: Carbonaceous rocks.

From the very nature of sedimentary processes the principal kinds of sediments tabulated above grade into each other, and frequently it is difficult, if indeed not impossible, to determine whether a particular rock should be placed in one division or in another.

I. Sedimentary Rocks of Mechanical Origin

The rocks of this class have resulted mainly from the mechanical action of water, less often from the action of wind, and are therefore stratified (arranged in layers or beds). With few exceptions, they represent the land waste derived by weathering of preëxisting rocks, transported and deposited by moving waters, and subsequently consolidated. Because they are composed of fragments of preëxisting

[1] Rocks and Rock Minerals.

rocks they are sometimes referred to as *fragmental* or *clastic* sediments. In composition they are chiefly siliceous and argillaceous, sometimes calcareous. In texture they vary from very coarse to very fine-grained rocks, and may frequently contain fossils — remains of animals and plants. They are described below under *breccias, conglomerates, sandstones,* and *shales.*

Breccias. — Breccias are composed of angular instead of rounded fragments, cemented together into solid masses (Figs. 51, 54). They

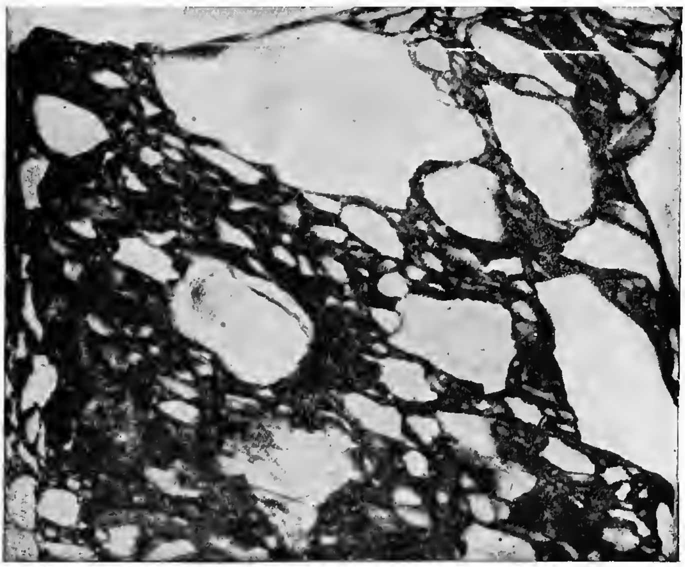

FIG. 54. — Breccia formed by crushing of marble by rock movements.

are not, strictly speaking, water-laid rocks, as shown by the angular character of the fragments, and usually absence of stratification. When deposited in water, as they sometimes are, the character of the fragments clearly indicates that they have not been moved by running water any distance from their source. They have not all been formed in the same way, and we may distinguish, on the basis of origin, the following kinds: (1) *Talus breccias,*[1] composed of angular material (Fig. 55), derived by disintegration, which accumulates at the base of cliffs (Fig. 55), and sometimes becomes cemented from the action of circulating waters. (2) *Friction* or *fault* breccias, formed of angular material derived from earth-movements which crush and

[1] See further regarding these under Weathering, Chapter IV, and Landslides, Chapter VII.

break up the rock on the two sides of a fault by rubbing of the walls against each other, or by intense crushing (Figs. 108, 109), incident to folding.[1] The coarse and fine angular fragments so derived are often cemented together by deposition from circulating waters. Of the substances deposited in the interstices of the rock fragments and which serve to bind them together, calcite or dolomite, and quartz, are probably the commonest. Sometimes ore-minerals are deposited by the circulating waters along with the common non-metallic ones, which give rise to breccia-ore deposits, such as the zinc deposits of

Fig. 55. — Talus breccia formed by disintegration of limestone seen in cliffs on right, Lake Louise, Alberta. (J. S. Hook, photo.)

southwest Virginia and east Tennessee. (3) *Volcanic* or *eruptive* breccias, formed from the coarse and fine angular material erupted by volcanic action, and afterwards consolidated into solid rock. If of recent formation volcanic breccias are usually very porous. (4) *Fold* breccias, formed by the crushing of rocks during folding. (5) *Solution* breccias, formed for example where the lime carbonate of a cherty limestone is removed by solution, the chert fragments gathering together as the mass settles.

The angular fragments composing breccias may vary greatly in size, ranging from large irregular-shaped blocks down to rock particles just large enough to be readily distinguished by the naked eye. These

[1] The term *autoclastic* may be applied to rocks shattered by movements within the earth's crust.

different sized materials may be and usually are heterogeneously mixed. The fragments may all be derived from a single rock type — igneous, sedimentary, or metamorphic — or from several dissimilar types. When derived from a single kind of rock, the breccia may be so named as *limestone* or *marble breccia, quartzite breccia,* etc.

Breccias may show a wide range of color, due partly to kind and color of the rock fragments and partly to the character and amount of the cement. They have not been used to any extent as a stone for building purposes, chiefly because of their heterogeneous character and appearance, but some of the more compact varieties which are

FIG. 56. — Coarse conglomerate with little cement, Frank, Alberta. (H. Ries, photo.)

susceptible of a polish are of great ornamental value, such as some of the brecciated marbles (Fig. 54). These, however, are often lacking in durability and may be of very irregular hardness.

Conglomerates. — These are composed of rounded and water-worn material of different sizes (Fig. 56), ranging up to large boulders, cemented together into solid rock (Fig. 52). The pebbles are rounded from water action. They are usually made up of the more resistant minerals and rocks that may have traveled some distance from their original source, and the interstices are commonly filled with fine sediment, such as sand, etc. Among the commonest cements binding the pebbles together are silica, calcite, and iron oxide. The pebbles may be of a single kind of mineral or rock, or several kinds may be mingled

together. Thus, we may have *quartz conglomerate, limestone conglomerate,* etc.

The rock pebbles composing conglomerates may be derived from igneous, sedimentary, or metamorphic rocks. *Volcanic conglomerate* is composed of igneous material ejected during volcanic activity that has fallen into water and become rounded and cemented into solid rock.

Like breccias, conglomerates are subject to a wide range of color, and texturally present a heterogeneous appearance. The ratio of cement to pebbles is very variable. Conglomerates showing much cement and with sharp contrast between it and the pebbles have received the name *pudding stone.* Nearly all gradations between conglomerates and sandstones may be observed.

Conglomerates are aqueous rocks and are usually deposited in shallow water close in to shore. They may sometimes represent stream deposits. Bedded structure is apt to be less distinct in the coarser types. They usually mark the lower member of a sedimentary series, indicating advance of the sea over the land, resulting in unconformity (p. 143). They are of widespread occurrence among sedimentary rocks.

Some conglomerates may furnish durable building material, but on account of their heterogeneous character and general coarseness, they have not been employed to any extent either as a building or ornamental stone. The harder and denser conglomerates have sometimes been used for making millstones.

Sandstones. — Sandstones are composed of grains of sand cemented together. Many sandstones contain little if any cement, and hence show little tenacity. The component grains are chiefly quartz, but other minerals occur, such as feldspar, mica, garnet, magnetite, etc. Size of the individual grains varies, the coarser-grained sandstones passing into conglomerates on the one hand, and the finer-grained ones into shales on the other. Only the medium and fine-grained sandstones are used, as a rule, for building purposes.

Sandstones exhibit a variety of color, the various shades of gray, white to buff, brown, and red being the most common. The color of sandstone and its adaptability depend more perhaps upon the character of the cementing material than upon the individual grains. Silica alone yields a light-colored, durable rock, but one that is hard and difficult to work, while sandstones cemented with iron oxide are some shade of red or brown and usually work readily. A calcium carbonate cement produces a light-colored rock, generally softer and less resistant to the weather, but easy to work. Clay cement if abundant is

objectionable because of the readiness with which it absorbs water, rendering the rock subject to injury by frost. The color of sandstone is often one of the factors governing its use as a building stone.

The porosity of a sandstone is a matter of practical importance for several reasons. High porosity may mean high absorption and high permeability. A very porous sandstone might therefore be regarded as unsuitable for dam construction or for use in moist situations.

Fig. 57. — Section in hard sandstone (quartzite) showing horizontal stratification, Ausable Chasm, N. Y. (H. Ries, photo.)

If the absorbed water completely fills the pores there is danger of the stone disintegrating when exposed to repeated freezing.

Porous sandstones under favorable structural conditions often serve as reservoirs for artesian water, oil and gas.

The absorption of sandstones ranges from less than 1 per cent in the dense ones to more than 10 per cent in the porous ones. The average crushing strength will range from 9,000 to 12,000 pounds per

square inch, but may be considerably higher if the rock is quartzitic in character. The fire resistance of sandstones is fair.

Sandstones rank among the most important of natural building materials and are widely distributed both geologically and geographically. Those found in the older geologic formations are usually harder

FIG. 58. — Beds of gently dipping shale, overlain by hard, much-jointed sandstone. The boundary line is very distinct. Sydney, N. S. (H. Ries, photo.)

and denser than those occurring in the younger ones. The chief use of sandstone is for structural work, and it is locally quarried at many places. Certain sandstones are of value for making grindstones and pulp stones, while those running high in silica and low in iron may be crushed and sold to the glass manufacturers.

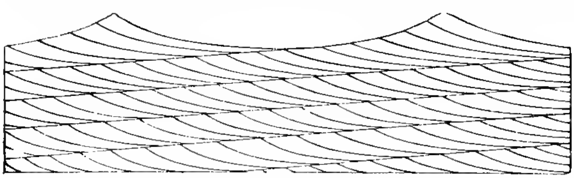

FIG. 59. — Section illustrating cross-bedding.

Aqueous sandstones are deposited in beds or layers of varying thicknesses, and when laid down in shallow water, rapid changes in currents or eddies frequently produce cross-bedded structure (Fig. 59).

Varieties of sandstone are based chiefly upon the character of cementing material, composition, structure, etc. Named according to the character of cement we may recognize *siliceous*, *ferruginous*, *calcareous*, and *clayey* or *argillaceous* sandstones. Other varieties are: *Arkose*, a sandstone containing much feldspar; sometimes called *feldspathic*

sandstone, derived from weathering of feldspathic rocks, especially granite, the products having been moved only short distances. *Graywacke*, a compact, usually gray sandstone (fine conglomerate) composed of rounded or angular fragments of various kinds of rocks in addition to grains of different minerals. *Flagstone*, a variety of thin-bedded sandstone which splits readily along the bedding planes into slabs that may be used for flagging. *Freestone*, a variety of sandstone, usually thick-bedded, that works easily or freely in any direction. *Micaceous* sandstone, a variety containing much mica.

Sandstones of low absorption and superior hardness are, as a rule, of high durability, but some of the softer ones may disintegrate under frost action. Clay seams are a source of weakness, and mica scales if abundant along the bedding planes are liable to cause flaking of the stone when exposed to repeated freezing, especially if it is set in the wall on edge.

Shales. — Shales are compacted clays, muds, or silts that possess a thinly laminated or fissile structure. The structure is true stratification or bedding which has resulted from deposition of the finely-divided material in water. Because of being composed of the finest particles of land waste shales are capable of being split into very thin leaves, the component minerals of which are too small to be determined by the naked eye.

Shales exhibit a variety of color, gray, buff, yellow, red, brown, purple, and green to black, being frequently observed. They are usually soft and brittle rocks, which crumble readily under the hammer. They may grade into clays on the one hand, and into fine-grained sandstones when siliceous, into thin-bedded limestones when calcareous, into some kinds of coal when carbonaceous, etc., on the other. No sharp line of division can therefore be drawn on the basis of physical properties, chemical composition, or name between shales and other rocks into which they grade. When metamorphosed shales may pass into slates and schists. Shales are much less impermeable to water than sandstones. The dense ones average in weight about 150 pounds per cubic foot.

Many varieties of shales are recognized, the distinction being based chiefly on composition. Thus, we may have *argillaceous* or *clay* (*aluminous*), *arenaceous* or *sandy* (*siliceous*), *calcareous*, *ferruginous*, *carbonaceous* or *bituminous* shales, etc.

Shales are not as strong as sandstones or hard limestones, and for this reason, if unsupported or enclosed, they yield to the pressure of overlying rocks. This is occasionally noticed in coal mines, where after the removal of the coal the shales of the floor and roof some-

times squeeze together. For the same reasons, shales which have been crushed and fractured by earth movements may yield to the pressure of the surrounding rocks, so that the fractures become healed or closed up, and there is less chance for the circulation of underground waters. This fact must be considered in the construction of aqueduct tunnels to avoid danger from leakage.

Shales, because of their thin-bedded character, sometimes cause trouble in tunneling, the material becoming dislodged quite easily.

They are of no value as a building stone, but often find extended use in the manufacture of brick, tile, and sewer-pipe, and of Portland cement, the same as clays (see below).

Shales that have consolidated by pressure alone slake down to soft clay on exposure to weather, while those that have consolidated through cementation of the grains weather to scaly fragments. It is the former type that is most valuable in the manufacture of clay products.

Variation in shale and sandstone deposits. — Shales when followed along the bed sometimes grade into sandstones and *vice versa*, and moreover the two may alternate, sometimes in rapid succession. Fig. 58 shows a heavy sandstone bed underlain and overlain by shale. There are, however, many localities in which large deposits of either shale or sandstone alone are found.

The possibility of variation in sedimentary rocks, especially shales and sandstones, is an important point for engineers to bear in mind when searching for a convenient site to open a quarry for road material or dimension stone.

The case of the Ashokan dam referred to above (p. 55) can again be taken to illustrate our point. The dam is located in a region of sedimentary rocks consisting of sandstones and shales. The former are in part thin bedded and used for flagstones, and many quarries have been opened up in the thin bedded or "reedy" rock. In other parts of the formation in the same district more massive beds were found, which were suitable for the extraction of dimension blocks. As a matter of practical interest, it may be mentioned that the *reeds* or thin bedding were due to the presence of numerous small sized, elongated grains, lying in a more or less parallel position.[1]

Clay. — Clay resembles shale chemically and mineralogically and in most cases is of sedimentary origin. The typical clays are unconsolidated, but all gradations are found between these and hard shales, the intermediate forms being known as clay-shales.

Sedimentary or bedded clays vary in form and extent of the deposit,

[1] Berkey, Sch. of M. Quart., XXIX, p. 154, 1908.

depending on conditions of origin. Beds of clay may be extensive and of uniform thickness, or they may be lenticular. Indeed they show the same variations as shale deposits.

Kinds of clay. — Many kinds of sedimentary clay are known by special names, which in some cases indicate their use but in others refer to certain physical properties. Those of interest or importance to engineers are: *Adobe*, a sandy, often calcareous clay used in the west and southwest for making brick. *Brick clay*, any common clay suitable for making ordinary brick. *Fire clay*, one capable of standing a high degree of temperature, not less than 1700° C. *Gumbo*, a very sticky, highly plastic clay, of dark color, occurring abundantly in the central, western, and southern states, and sometimes burned for making railroad ballast or road material. *Loess*, a sandy calcareous clay covering large areas in the Great Plains region. *Paving brick clay*, one capable of burning to a vitrified body at a moderate temperature for use in paving brick manufacture.

Uses of clay. — The important engineering uses of clay are for making Portland cement, burned clay products, and roads (Chapter XI).

The following analyses show how clays may vary in their chemical composition.

Analyses of Clays

	1	2	3	4	5	6	7	8
Silica (SiO_2)	46.3	45.78	44.76	57.62	59.92	68.62	38.07	90.00
Alumina (Al_2O_3)	39.8	36.46	38.41	24.00	27.56	14.98	9.46	4.60
Ferric oxide (Fe_2O_3)	......	0.28	0.63	1.9	1.03	4.16	2.70	1.44
Ferrous oxide (FeO)	......	1.08	......	1.2	......	......	......	......
Lime (CaO)	......	0.50	0.20	0.7	tr.	1.48	15.84	0.10
Magnesia (MgO)	......	0.04	0.09	0.3	tr.	1.09	8.50	0.10
Potash (K_2O)	......	0.25	0.35	0.5	0.64	3.36	2.76	tr.
Soda (Na_2O)	......		0.09	0.2				tr.
Titanic oxide (TiO_2)	......	......	1.37	......	......	......	......	0.70
Water (H_2O)	13.9	13.40	13.46	10.50	9.70	3.55	3.49	3.04
Moisture	......	2.05	1.22	2.7	1.12	2.78	......	......
Carbon dioxide (CO_2)	......	......	......	......	......	......	20.46	......
Sulphur trioxide (SO_3)	......	......	......	0.35	......	......	......	......
	100.00	99.84	100.58	99.97	99.97	100.02	101.28	99.98

1. Kaolinite; 2. Washed kaolin, Webster, N. C.; 3. White sedimentary clay, Dry Branch, Ga.; 4. Plastic fire clay, St. Louis, Mo.; 5. Flint fire clay, Salineville, O.; 6. Red-burning brick clay, Guthrie Center, Ia.; 7. Cream-burning, calcareous brick clay, Milwaukee, Wis.; 8. Sandy brick clay, Colmesneil, Tex.

Road materials. — The use of clay for road-making purposes is discussed in Chapter XI.

Portland cement. — Clay used in the manufacture of Portland cement should be as free as possible from gravel and sand, calcareous concretions, gypsum, and pyrite nodules. Silica should run preferably between 60 and 70 per cent, and the ratio of (Al_2O_3 + Fe_2O_3) to SiO_2 should be about 1 to 3. Magnesia and alkalies should not exceed 3 per cent if possible. High alumina clays are undesirable, but the

presence or absence of lime is of no importance. White-burning clays are sometimes used to make a white Portland cement.

Clay products. — Clay is of great importance in the manufacture of burned clay products, such as building and paving bricks, hollow blocks, sewer pipes, electric conduits, and sewer pipe, as well as other products not specially used by the engineer. Its value for this purpose depends primarily upon two properties, namely, that of plasticity when wet, which permits it to be molded into any desired shape, and that of hardening to a rock-like mass when exposed to a temperature

Fig. 60. — Section showing fire clay underlying coal seam. The upper clay above coal is of impure character.

of at least redness. Other properties such as porosity and hardness after firing, refractoriness, shrinkage, and color when burned must also be considered.

Relation of clay to engineering work. — Clay is easily excavated but, when wet, it is inclined to slide if unsupported (Chapter VII), and in this condition is apt to flow under load. A variable amount of swelling may accompany the absorption of water, this being sometimes sufficient to force retaining walls or other objects out of place.

Dry clay will usually maintain an upright face unsupported and, where a high face of it is exposed in a bank or road cut, its stability may be preserved by (1) maintaining a very low slope, (2) under-

ground drainage, or (3) benching the face of the bank if the clay is sufficiently dry.

Wind (Æolian) Deposits

Under this head are included *loess* and *dune sand.* Probably *loess* should be included only in part, since it is not agreed by all that wind has been the principal agent involved in the formation of all deposits.

Loess. — Loess is the name given to very fine, homogeneous, clay-like compact material that is largely siliceous in composition, but contains calcareous matter, which may form nodules and small vertical tubes. It is usually characterized by absence of stratification, but cleaves vertically, so that when eroded it forms steep precipitous cliffs. It is composed chiefly of clay-like material and sharply angular grains of quartz, feldspar, mica, and other minerals. Carbonate of lime has been reported in some cases to reach 30 per cent in amount.

Loess covers vast areas in many parts of the world, reaching a thickness of hundreds of feet in some cases, and for this reason is of some importance to the engineer. Some of the larger and more important areas of loess include the Mississippi Valley in the United States, the valleys of the Rhine and its tributaries in Europe, and northern central China in Asia. In origin it is claimed by some to be æolian, by others to be fluviatile or lacustrine, and by still others to be partly æolian and partly aqueous (Chamberlin and Salisbury). When exposed to rainstorms loess often gullies very badly. It is widely used in many parts of the West for common-brick manufacture.

Sand deposits. — The name sand refers to size of grain and not to mineral composition. The prevailing kinds are composed of the harder varieties of rocks and minerals, since the softer ones tend to break up by abrasion and decomposition into finer particles known as *dust.* The diameter of individual sand grains may vary within the limits of 1 to 0.05 millimeter; above this size sand grades into gravel and below into silt and clay. The sand grains may consist of any kind of mineral or rock, the former being more common, and their composition will depend upon the kind of rock from which they were derived. Because of its hardness, resistance to chemical agents, and abundance in rocks, quartz is the commonest mineral in sand, but many other minerals may be present. Thus we have sand deposits of sedimentary origin, composed almost entirely of such minerals as magnetite, gypsum, calcite, dolomite, glauconite, etc.

Sand in some cases is simply the product of rock disintegration by weathering, but in other instances, mixed products of weathered rock may be removed by streams, glacial ice, or wind, the materials of

different size being sometimes separated and sorted, and the sand becoming concentrated by itself. Other sands may originate by the grinding action of waves along the coast. Only wind-blown or æolian sands are treated here in detail.

The coarse stream or sea sands, depending upon the amount of transportation, are frequently more or less rounded from wear, while the finer particles protected by a film of water are likely to be angular or subangular. Glacial sands, when not subsequently modified by water action, are angular, while wind-blown sands are apt to be

Fig. 61. — Front slope of advancing sand dune. Shows edge of forest lying in its path, and trees already partly buried. Cape Henry, Va. (T. L. Watson, photo.)

rounded. Beach sands formed by the sea and carried inland by the wind may be angular or subangular, and do not, as a rule, show the well-rounded form of desert sands.

Sand dunes. — In arid and semi-arid regions, and in humid regions where the loose sand is not protected by vegetation, especially beaches of sea and lake shores, the sand is piled up by the driving action of the wind into mounds and ridges called *dunes* (Figs. 61, 62). The sand particles are lifted only a slight distance above the land surface, hence their movement is often interfered with by obstacles, such as a tree, shrub, building, fence, etc., which results in deposition and accumu-

lation. The ridges commonly lie transverse to the direction of the wind, but may sometimes be longitudinal or parallel. They are usually not more than 10 or 20 feet high, but sometimes reach heights of 200 or 300 feet.

Dunes commonly show a long, gentle slope, on the windward side, up which the sand grains can be readily moved, and a steep slope (angle of rest for the sand grains) on the leeward side (Fig. 63). The slopes may be very irregular when the dunes are partly covered by vegetation. Dunes migrate by the transfer of sand from their wind-

FIG. 62. — General view of sand-dune area. Shows grass and seedling pines which have been planted to stop the drifting sand. Baltic coast of Germany. (H. Ries, photo.)

ward to their leeward side, and may invade forests and fertile fields, and even bury villages, which may result in either case in much loss.

Sand dunes are abundant along many parts of the Atlantic and Pacific coasts, along the shores of the Great Lakes, and in many parts of the arid regions of the west.[1] They are not unknown in some of the sandy inland areas of the United States.

Wherever found they are often a source of trouble if the region is an inhabited one, since in their march across country they bury houses, forests, orchards, railroads or anything in their path. Along some railways crossing dune territory, the sand which drifts across the tracks has to be removed daily.

[1] Hitchcock, Nat. Geog. Mag., XV, p. 43, 1904; Kellogg, Cal. Jour. Tech., III, p. 156, 1904; Stuntz and Free, U. S. Bur. Soils, Bull. 68, 1911.

The practice of "fixing" dunes, to prevent troubles such as those mentioned, is a problem for engineers and others, which has been but little dealt with in some parts of the United States, although it has gone on in Europe for more than 50 years.

The preliminary methods used for "fixing" dunes are: (1) Transplanting with beach grass; (2) covering with heather; and (3) covering with a network of sand hedges. Any one of these methods serves

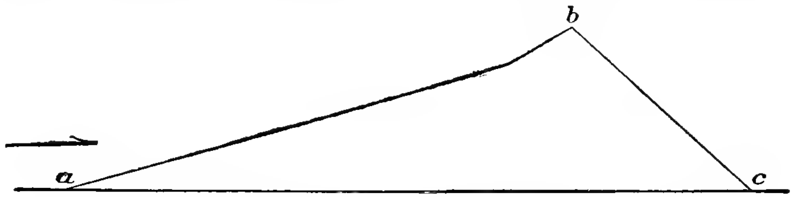

FIG. 63. — Section of a dune showing long, gentle, windward slope (*ab*) and steeper leeward slope (*bc*).

to hold the sand temporarily, after which young trees, usually conifers, are transplanted, and the danger of shifting is soon removed. (Fig. 62.)

Some railroads have adopted the plan of temporarily fixing the dunes by spraying them with crude oil.

Uses of sand. — Siliceous sand is extensively used for mixing with cement or lime to make concrete and mortar, for filtration purposes, road making (clay-sand roads), sand-lime brick, mold cores, glass, etc. Sands found in the glacial drift may contain mineral and rock grains other than quartz, which make them less desirable for some purposes.

Magnetite sands, if in large deposits, might be used in iron manufacture, but in most cases they are of limited extent. Gypsum sands can be used for plaster manufacture, but the known deposits in the west are not favorably located. Glauconite sands (green sand) have been employed to a slight extent as fertilizer, while the monazite sands of Brazil, India, and North Carolina serve as sources of some of the rare earths, especially thorium, which is used in the incandescent mantle industry.

II. CHEMICAL SEDIMENTS FORMED FROM SOLUTION

Deposits of this class owe their origin to chemical processes, and have formed chiefly by concentration of aqueous solutions, changes of temperature, loss of carbon dioxide, etc., aided more or less in some cases by the action of organisms (plants and animals), and resulting in the precipitation of insoluble salts.

Sulphates

Gypsum and Anhydrite.—Gypsum and anhydrite, described as minerals on pages 21 to 22, are usually intimately associated in occurrence and origin, and can be discussed together. Gypsum of commerical importance may occur as rock gypsum, gypsite, or gypsum sand. The gypsum frequently disseminated as crystals, concretions, or plates in some clays and shales is of no commercial value.

Gypsum and anhydrite may occur as separate and independent bodies interbedded, or in irregular masses, or the one may form veins traversing the other, and each may be transformed into the other. Their most important occurrences include beds or lenticular sheets and masses, interstratified usually with clays, shales, sandstones, and limestones, and in some regions are often associated with rock salt.

FIG. 64. — Map showing distribution of gypsum in the United States. (From Ries' Economic Geology.)

Large deposits of gypsum and anhydrite are known at a number of localities in the United States (Fig. 64) and Canada. They have been formed on a large scale from concentration of ocean waters by evaporation, and in inland lakes in which evaporation equals or exceeds the amount of inflow.

In some regions, the solubility of the gypsum produces a hummocky topography and even sink holes. The change of anhydrite to gypsum may occur on exposure of the former to moisture, and in Europe at least one case is known where a tunnel was driven through a deposit of anhydrite and thrown out of alignment caused by the swelling of the

material when changed to gypsum, the alteration being brought about by trickling water.

Uses. — Gypsum is widely used for the manufacture of *plaster of Paris,* cement plaster, wall plaster, as a retarder in Portland cement, in making plaster boards and blocks, and in other industries not of an engineering character. Anhydrite is of little or no commercial importance.

Gypsum varies in composition, due to the presence chiefly of clayey, siliceous, and calcareous impurities, as the following analyses will show.

ANALYSES OF GYPSUM

	Pure gypsum.	Dillon, Kan.	Alabaster, Mich.	Grand Rapids, Mich.	Saltville, Va.	Gypsite, Marlow, Okla.	Gypsite, Burns, Kan.	Gypsite, Salina, Kan.	Gypsite, Dillon, Kan.
$CaSO_4$	79.10	78.40	78.51	76.26	72.06	59.46	67.91	34.38	56.58
H_2O	20.90	19.96	20.96	20.84	21.30	16.59	17.72	8.50	15.16
SiO_2	....	0.35	0.05	tr.	1.68	10.67	2.31	34.35	17.10
Al_2O_3 and Fe_2O_3	....	0.12	0.08	0.54	1.95	0.60	0.37	4.11	2.04
$CaCO_3$	....	0.56	....	n.d.	....	10.21	11.71	8.14	7.71
$MgCO_3$	....	0.57	0.11	n.d.	....	1.10	0.52	10.52	1.24
	100.00	99.96	99.71	97.64	96.99	98.63	100.54	100.00	99.83

The use of gypsum in different kinds of plaster depends on the fact that when the pure material is heated to a temperature between 250° and 400° F. it loses about three-fourths of its water of combination, the calcined product being known as *plaster of Paris.* This, when mixed with water, takes up in chemical combination as much as it has lost, and sets rapidly to a hard mass. The presence of impurities retards the setting, and such slow-setting plasters are known as *cement plasters.* Gypsum heated above 400° F. is called *dead-burnt* plaster, and lacks the usual setting qualities, but if heated to about 900° F. and finely ground, it sets slowly to a hard product (*flooring plaster*).

Chlorides

Rock salt. — Halite occurs in many localities as beds of rock salt, interstratified with clays, marls, and sandstones, usually associated with gypsum, anhydrite, and dolomite. The celebrated salt deposits of Stassfurt, Germany, associated with gypsum, anhydrite, and the chlorides and sulphates of potassium and magnesium, are among the largest in the world, having a known thickness of 4000 feet. Beds of rock salt also occur in New York, Kansas, Michigan, Louisiana, Virginia, and many other states. In many cases the formation of rock salt has been similar to that of gypsum.

Salt deposits are of no special importance to the engineer. Owing to their ready solubility they are rarely found outcropping on the surface except in arid regions, and their solution may cause surface settling. Their presence is sometimes noted by surface waters in some regions showing an abnormal chlorine content caused by the drainage from salt-bearing formations entering surface streams. Saline water in a deep well, however, does not necessarily indicate the presence of salt beds.

Siliceous Deposits

Under siliceous materials are included those deposits of silica (SiO_2) which form by deposition from evaporation of aqueous solutions, and by the action of organic life. Some may form at times as the result of direct chemical reactions. Such deposits have not the widespread occurrence and importance as sediments formed by other processes, but are sometimes of considerable interest locally, such as *flint, siliceous sinter* (*geyserite*), and *diatomaceous earth.*

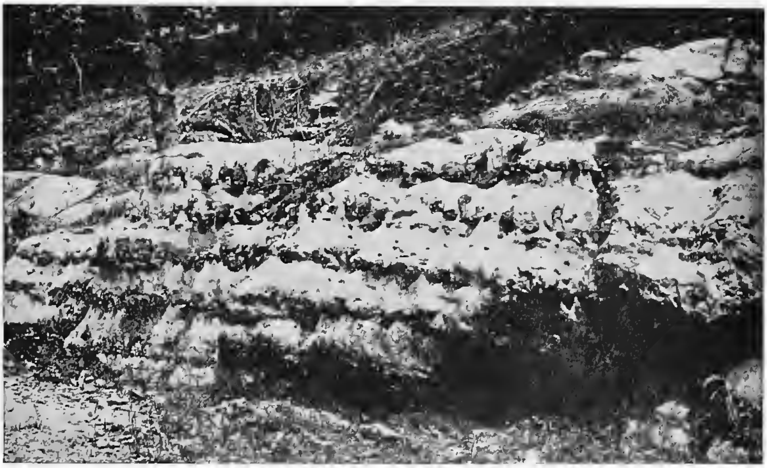

FIG. 65. — Cherty limestone, 6 miles west of Lexington, Va. The chert nodules stand out in relief on the weathered surface. (After Bassler, Bull. II–A, Va. Geol. Surv.)

Flint. — Flint, known also as *chert* and *hornstone* and referred to as a variety of quartz (Chapter I) is a hard, dark gray to black rock, breaking with conchoidal fracture, and composed of amorphous or chalcedonic silica. Its dark color is due to carbonaceous matter, which disappears on strong heating. It is translucent on thin edges, resembling many felsites of igneous origin. Chert occurs chiefly as nodules, layers or lenses in chalk and limestone (Fig. 65) and is especially common in many of the dolomitic limestones of the United States. In building stones flint is a disadvantage; because of its superior hardness to the surrounding rock, it interferes with the cutting of it. Also, when cherty rock is exposed to the weather, it stands out in relief on the surface because of its greater resistance, as well as sometimes causing the stone to split along the lines of concretions. It is undesirable in limestones used for cement manufacture. Chert

is extensively used as a road material in some southern states. The chert used in ball and tube mills is obtained from the chalk formations of Germany, England, etc.

Jasper, a ferruginous opaline silica, occurring as large masses in the iron formations of the Lake Superior region and known as *jaspilite*, is also a variety of flint, and the *novaculite*, occurring in extensive beds in Arkansas, and used in the manufacture of whetstones and hones, is still another one. Jasper also occurs in considerable quantities associated with the zinc ores of southwest Missouri.

Geyserite. — This, known also as *siliceous sinter*, is amorphous silica deposited from solutions of evaporating hot waters in volcanic regions, and by silica secreting algæ. It is most extensively developed in the United States in the hot-spring and geyser region of the Yellowstone National Park. At Steamboat Springs, Nevada, there are extensive deposits of siliceous sinter which contain traces of antimony and mercury.

Diatomaceous earth. — Diatomaceous earth, known also (but incorrectly) as *infusorial earth* or *tripolite*, is a soft, pulverulent, siliceous clay-like material, very fine and porous in texture, somewhat resembling chalk, bog-lime, or kaolin in its physical properties, and of white, yellow, or gray color. It can be readily distinguished from chalk and bog-lime by not effervescing in acid and from kaolin by its distinct gritty feel and lighter weight. It is formed from the shells or tests of certain aquatic microscopic forms of plant life known as diatoms and the accumulations on the bottom of ponds are occasionally mistaken for bog-lime.

Diatomaceous earth is used to a small extent as a polishing powder and as a packing for insulating heated pipes. When mixed with a small amount of clay it can also be made into hollow blocks for partitions, for which purpose it serves as an insulator against heat and sound.

Ferruginous Rocks (Iron Ores)

There are many sedimentary rocks, especially sandstones, conglomerates, and shales, which contain considerable iron oxide as cement binding the grains together, and which strictly speaking are ferruginous rocks. On the other hand, there are others which are made up largely of the oxides (*hematite*, *limonite*, and *magnetite*), or the carbonate (*siderite*, or *spathic iron ore, clay iron stone*, and *black band ore*), many of which contain sufficient iron to be worked as an ore of the metal, but nevertheless are classed as sedimentary rocks.

Limonite in the form of nodules or as more or less continuous beds is sometimes precipitated on the bottom of ponds or lakes, or even in the sea.

Hematite has been rather extensively developed in the form of bedded deposits in several different geologic periods, the formations being of great extent in some cases. Its formation may be due to either chemical or organic agencies, or probably both. Prominent examples of this type are the Clinton iron ores which extend from New York to Alabama.

Magnetite is not usually found in bedded deposits. It may be an important constituent of some sandstones, in which it is probably of mechanical origin.

Siderite sometimes forms bedded deposits in association with carbonaceous shales and clays (p. 66).

Carbonate Rocks

This group of rocks is composed essentially of carbonate of lime, or of this substance with carbonate of magnesia. They vary greatly as to purity, color, and texture; are readily soluble in cold or hot hydrochloric acid; and are easily scratched with the knife, their hardness being under 4. In mode of formation they are partly organically and partly chemically derived rocks. Fragmental calcareous deposits result from the mechanical breaking down of original masses and redeposition of the débris, such as coral sands, etc.

Limestone. — This is the most important, and widely distributed of the carbonate rocks. It is composed of calcium carbonate of varying degrees of purity (see table of analyses, p. 77), the more common impurities being magnesia, silica, clay, iron, and bituminous or organic matter. These may be present in amounts sufficient to give character to the rock, when it may be designated magnesian or dolomitic, siliceous, argillaceous, ferruginous, or bituminous limestone. Limestones vary in color according to the character and amount of impurities present. When pure the rock is white, but the various shades of gray to black are the most common colors, while many others are known. Those of black or dark gray color sometimes fade slightly on prolonged exposure to the atmosphere.

The limestones show equally great variation in composition. The following table shows the variation in composition of limestones.

Analyses of Limestone

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.
SiO_2	......	......	0.72	0.06	3.83	0 08	5.5	7 60	6.22	28.72	15 37
Al_2O_3 ...	.....	......	1.5	0.80	2.31	0.25	1.3	0.75	1.70	12.28	9.13
Fe_2O_3....									0.86	5.22	2.25
CaO.....	56.00	30 44	54.28	55.00	52.16	30.46	28.2	50.05	47.86	25 54	25.50
MgO.....	.....	21.73	0.8	.....	0.14	21.48	20.2	0.30	0.04	1.10	12 35
CO_2......	44.00	47.83	44 0	43.22	41.64	47.58	44.3	41.30	42.11	24 40	34 20
H_2O.....	......	......	......	.....							1.20
SO_3......	......	......	......	0.05	0.20	.....	.....	......	......	1.53	n.d.
Total..	100.00	100.00	101.30	99 13	100.28	99.85	99.5	100.00	98.79	98 79	100.00

I. Calcite; II. Dolomite; III. Pure limestone, Smith's Basin, N. Y.; IV. Bog lime, Newaygo, Mich.; V. Chalk, Western P. C. Co., Yankton, S. D.; VI. Dolomite, Canaan, Conn.; VII. Magnesian limestone, Oxford Furnace, Sussex County, N. J.; VIII. Hydraulic limestone, Malain, France; IX. Impure bog lime, Montezuma, N. Y.; X. Natural cement rock, Cumberland, Md.; XI. Natural cement rock, Rondout.

From this table it will be seen that limestones range from rocks composed almost entirely of calcium carbonate or of calcium and magnesium carbonates, to others which are high in clayey and siliceous impurities. The presence of clayey impurities not only gives the rock an earthy appearance, but at times even a shaly structure. Chemical composition is of importance if the stone is to be used in cement manufacture, for flux, or in the chemical industries.

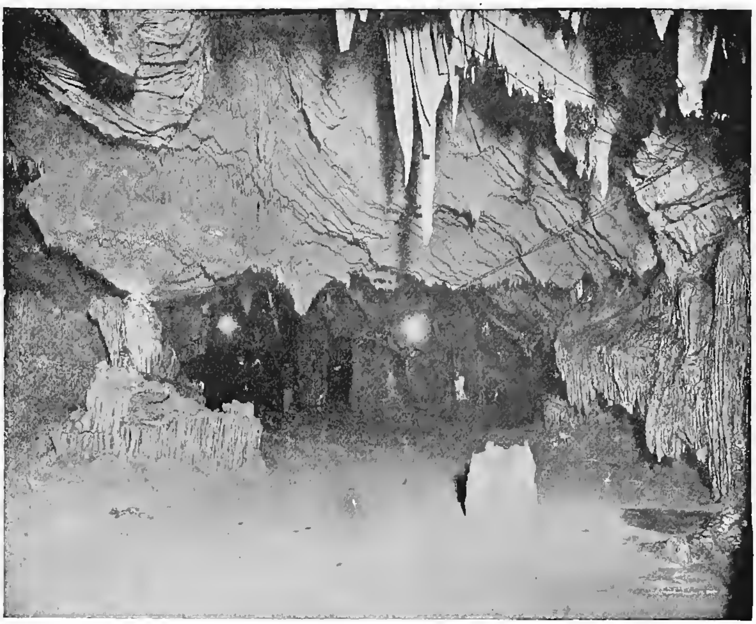

FIG. 66. — Weyers Cave, Va., showing stalactites of lime carbonate suspended from the roof.

The compact calcitic varieties vary in specific gravity from 2.5 to 2.8, effervesce freely in cold dilute acid, and can be readily scratched with a knife.

Variations of limestones in texture, strength, porosity, and durability are as great as in composition. They may vary from very fine-grained and compact rocks to those composed of coarse fragments of shells or coral. Those found in the older geologic formations are usually of low porosity, but the younger ones are often very porous. Most limestones show a crushing strength of from 9000 to 12,000 pounds per square inch, but some hard ones exceed this considerably, and a few much used soft ones run as low as 3500 pounds. The

absorption of most hard limestones is usually under 2 per cent, but some widely used ones like that from Bedford, Indiana, show 4 or 5 per cent, and the French Caen stone, 10 to 12 per cent. The weight per cubic foot of limestones ranges from about 120 to 170 pounds.

Limestones are found in beds of all thicknesses up to 100 feet or more. They weather chiefly through solution, the soluble calcium carbonate being removed and the insoluble material (clayey and siliceous impurities) left in place to form residual soils (see Chapter IV). If, however, the rock approaches dolomite in composition and is crystalline granular in texture it weathers chiefly by disintegration.

Solubility.[1] — The solubility of limestone is not alone a matter to be considered in connection with its resistance to weather, but also in engineering operations where limestone and water are in constant contact.

The question of imperviousness of a limestone may be closely related to its solubility, as has been demonstrated on several occasions in aqueduct construction. Where an aqueduct has to cross under a valley by a pressure tunnel, more or less loss may take place through the crevices in the rock, but if the rock is a soluble one like limestone, any crevices in it may become enlarged by solution with increasing leakage. This was noticed, for example, in the case of a 3-mile section of the Thirlmere (England) aqueduct, where a local limestone was used for concrete aggregate. A leakage amounting to 1,250,000 imperial gallons per day developed in a year, due to the limestone fragments becoming corroded by the water. Another instance was that of the limestone blocks used in building the old Delaware and Hudson canal, which showed the effect of contact with water. Here the blocks that had been in contact with the water for approximately 35 to 40 years had been etched until the fossils and other cherty constituents stood out from one eighth to one half inch beyond the general surface of the stone, and in some cases pits are an inch deep.[2]

Varieties of limestone. — Many varieties of limestone are recognized, based chiefly upon differences of composition, texture, etc. Most of these are used for structural purposes, which is to be assumed unless otherwise mentioned below.

Dolomite. — The name applied by many to those limestones which approximate the mineral dolomite in composition. Unfortunately the usage is not uniform and any magnesian-rich limestone is referred

[1] For other effects of water dissolving limestone see Weathering, Chap. IV, and Underground Waters, Chap. VI.

[2] Berkey, N. Y. State Museum, Bull. 146, p. 138, 1911.

to as dolomite. Between a straight calcic limestone and a pure dolomite, there may occur all gradations. Dolomite is similar in color, texture, and other physical characters to limestone, except that it is slightly harder, somewhat more resistant, because it is less soluble, and does not effervesce except feebly in cold acid. It is not always an original rock, but has sometimes been derived from straight calcic limestones by the substitution of magnesium carbonate for a part of the calcium carbonate — a process known as *dolomitization.* It is also used for flux and lime making.

FIG. 67. — Horizontally stratified limestone, Milwaukee, Wis. (From Ries, "Building Stones and Clay Products.")

Bog lime. — A white, powdery, calcareous deposit, precipitated through plant action on the bottom of many ponds, and used in Portland cement manufacture. It is often erroneously called *marl,* a term which properly belongs to a calcareous clay. *Shell marl* is an aggregate of shells of various organisms usually admixed with some clay or sand, and formed either in fresh or salt water,

Chalk. — A soft, porous, fine-grained variety of limestone composed chiefly of the minute shells of foraminifera. When pure it is white, though a variety of colors may be shown owing to the presence of impurities. It forms extensive deposits in France, Germany, and England, but is less abundant in the United States. Chalk is rarely used for structural purposes, but in some regions where it occurs it has been used as an ingredient of Portland cement. *Coquina.* — This term is applied to a loosely cemented shell aggregate, like that found near St. Augustine, Fla. The stone does not have a high strength nor is it of good durability if exposed to

severe weather conditions. It was used by the Spaniards for constructional work, and in the mild Florida climate has stood well. *Coral rock.* — A calcareous deposit consisting of coral reefs, coral fragments and shells, the entire mass being cemented

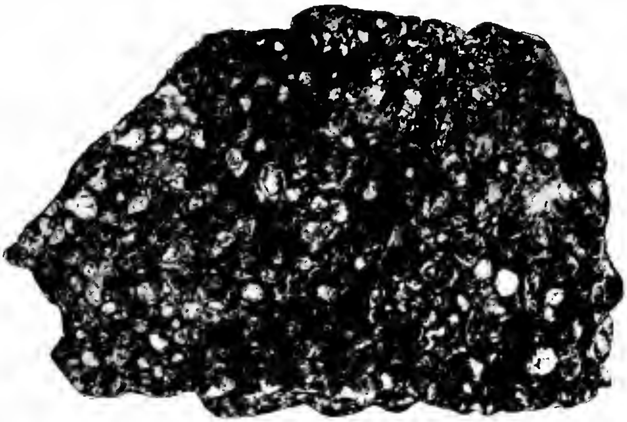

FIG. 68. — Pisolitic structure.

by lime carbonate. *Hydraulic limestone.* — A clayey limestone, used in cement making, but usually of no value as a building stone. *Lithographic limestone.* — This is a very fine-grained, homogeneous limestone, which because of its peculiar physical

FIG. 69. — Fossiliferous limestone, showing longitudinal and transverse sections of crinoid stems.

properties is of special value for lithographic but not structural work. *Oölite* or *oölitic limestone.* — A variety of the rock made up of small spherical or rounded grains of calcium carbonate, resembling fish roe in appearance, hence the name. When of coarser texture, the term *pisolitic* (Fig. 68) is employed. *Travertine, cal-*

careous tufa or *calc sinter*. — A name applied to the less compact, cellular or porous forms of limestone deposited by springs or streams. In this country no deposits of sufficient size for building purposes are known, but the stone is quarried in Italy. Small deposits are common in many parts of the United States, and some interesting ones are found around the Mammoth Hot Springs of the Yellowstone National Park. *Stalactites* and *stalagmites*. — Deposits of compact crystalline limestone, formed respectively on the roof and floors of caves, are forms of travertine (Fig. 66). Deposits formed on the floor of sufficiently massive character and extent to be cut are called *cave onyx*, although most of the *onyx marble* of commerce is a spring formation. Limestones may sometimes exhibit more or less conspicuously their fossiliferous character, when they may be named for the chief organic remains in them, such as *crinoidal*, *shell limestone*, etc. (Fig. 69).

Limestones in Engineering Work

Building stone. — Limestones, if sufficiently thick bedded, are widely used for building purposes, either as dimension or ornamental stone. It is chiefly the harder, denser, and finer-grained varieties that are sought, although the more porous ones of sufficient strength like the Roman travertine are sometimes employed.

Lime. — Limestone of either calcitic or dolomitic composition, but free from or containing but a small percentage of clayey impurities, is by decarbonation changed to quicklime, which is used in mortar.

Cement. — Those limestones containing an appreciable quantity of clayey and siliceous impurities do not possess slaking qualities when calcined, but on the other hand develop hydraulic properties after burning, as a result of which they set when ground and mixed with water. Three types of cement are recognized: (1) *Hydraulic limes* formed by the heating of a siliceous or argillaceous limestone to a temperature not much above that of decarbonation, the finished product having considerable free lime, because of the high percentage of calcium carbonate in the rock. (2) *Natural cements*, made from either calcitic or dolomitic limestones containing from 15 to 40 per cent of clayey impurities, fired to a temperature of dull redness so as to produce incipient fusion in the mass. (3) *Portland cement*, made from an artificial mixture of non- or low-magnesian limestone and clay or shale in the proportions of approximately three to one, the finely ground mixture being fired at a high temperature.

Road material. — Limestone is extensively used for road material as described in Chapter XI.

Foundations. — Hard limestone makes a good rock for foundations, although if used for dam or reservoir sites care should be taken to see that it is free from solution channels. Soft limestone like chalk is easy to excavate, but is rather friable, and weak as a base for structures subject to shock.

Fig. 70. — Map showing limestone areas in the United States. (After U. S. Geol. Survey.)

Tunneling. — Massive limestone makes a good rock for tunneling and should give no trouble provided it is free from solution channels which may let water into underground workings. If the limestone is cherty the hard lumps of chert will interfere somewhat with the speed of drilling. Folds, faults, abundant jointing, or shaly structure interfere with the solidity of the rock underground. (See Faults, Chapter III.)

Artesian water. — Artesian water is referred to in Chapter XI.

Distribution of Limestones. — Because of the wide distribution of limestone in the United States (Fig. 70) few areas have attained great importance as resources of supply. They are consequently worked at many localities for building stone, lime, or cement manufacture.

In the central states the Mississippian or Lower Carboniferous formation carries a number of important limestone deposits, of which that worked near Bedford, Indiana, is the best known. Much limestone is also obtained from the Devonian and Silurian formations. West of the Great Plains, although limestones are found at a number of localities, there are no such extensive areas of them as occur in the central and eastern states.

Phosphate Rocks [1]

These rocks, composed chiefly of calcium phosphate and known by the general term *phosphorite*, are of great value as a source of phosphoric acid in the manufacture of commercial fertilizers. While not uncommon, extensive beds are very much more limited in distribution than those of the common types of sedimentary rocks. They may be of chemical origin, the calcium phosphate having been precipitated from sea water, or of organic origin formed from organic remains, and in most cases have suffered further concentration of the phosphatic material, chiefly by solution and removal of calcium carbonate from the phosphatic limestone. They may be either compact, earthy, or concretionary, with pebble and nodular forms common. Some shade of gray is the commonest color. Large deposits are found in the United States in Florida and Tennessee, and in Idaho, Wyoming, and Utah, as well as in foreign countries.

Carbonaceous Rocks

Under this group of rocks are included those containing a high percentage of carbon and which are of organic origin. They are known as the *coal series.*

Origin and kinds of coal. — When vegetable matter decays under water out of contact with the air, it changes to a dark-brown or black cheesy mass, in which the vegetable tissue is partly destroyed and which is known as *peat.* This change is accompanied by loss of hydrogen, oxygen, nitrogen, and to a lesser extent carbon, all of which are constituents of plant tissues.

[1] For fuller discussion and bibliography, see Ries, "Economic Geology," 4th ed., 1916.

Peat, then, is a swamp formation, and vast accumulations of it have taken place in the past, especially during the Carboniferous, Cretaceous, and Tertiary times. When deposits of peat become buried under other sediments, it results in a compacting and hardening of the mass, together with a further chemical change, involving the elimination of additional hydrogen, oxygen, and nitrogen, and even some carbon. These products of burial whose formation involves exposure to both pressure and temperature are the true coals,

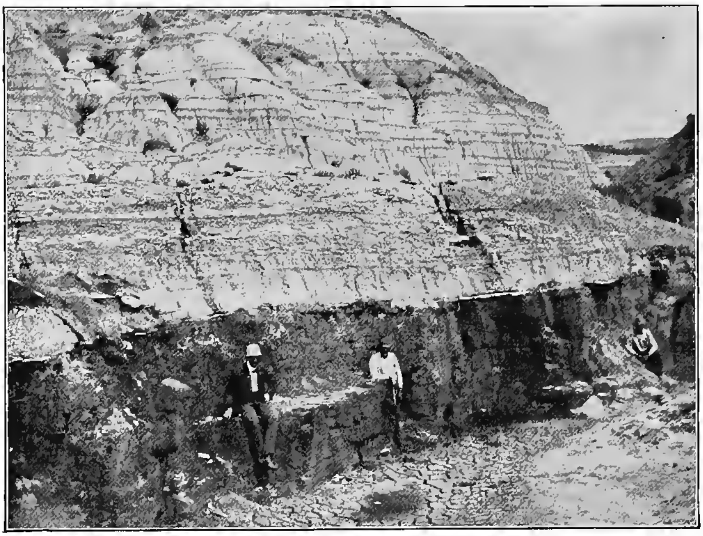

FIG. 71. — Outcrop of lignite, Williston, N. Dak. (Photo by Wilder, from Ries' Economic Geology.)

and they represent a progressive series, indicative of the amount of alteration which the vegetable matter has undergone. Although the change may be a gradual one, several types in the series are recognized, which named in their order from lower to higher rank are *lignite*, *subbituminous* coal, *bituminous* coal, *semibituminous* coal, *semianthracite*, and *anthracite*.

Composition and physical characters. — In passing from coals of lower to higher rank, the general changes noticed are (1) increase in density; (2) increase in carbon; (3) decrease in hydrogen, oxygen, and nitrogen; and (4) increase in luster.

The substances present in coal are not all in elementary form, but are often combined, so that the ordinary form of expression of the composition (proximate analysis)

of both the organic and inorganic materials present gives: Fixed carbon, volatile matter (chiefly hydrocarbons and oxides of carbon), moisture, ash, and sulphur.

Fixed carbon, volatile hydrocarbons, and free hydrogen are heating elements of the coal, and on account of the greater amount of the last named substance in bituminous coals, they may show greater heating power than anthracite. Volatile matter increases the free-burning qualities of the coal. Moisture, ash, and sulphur are undesirable constituents which stand in no direct relation to the rank of the coal, but affect its grade.

The following table gives the composition of coals of different ranks expressed in both elementary and proximate form:

ANALYSES OF COALS

Locality.	Proximate				Elementary						
	Moisture.	Volatile matter.	Fixed carbon.	Ash.	Sulphur.	Hydrogen.	Carbon.	Nitrogen.	Oxygen.	Calories.	B.t.u.
Peat, Orlando, Fla.	13.19	56.83	24.30	5.68	0.49	6.06	51.18	2.56	34.03	4961	.....
Lignite, Crockett, Tex.	13.40	42.75	29.00	14.85	1.04	5.57	52.06	0.95	25.53	5199	9,358
Subbituminous, Gallup, N. Mex.	8.13	34.82	37.83	19.22	1.30	5.05	56.71	0.98	16.74	5668	10,202
Bituminous, Huntington, Ark.	1.17	17.83	68.12	12.88	1.27	4.00	75.68	1.47	4.70	7450	13,410
Bituminous, Johnstown, Pa.	2.35	14.30	71.40	11.95	3.30	4.22	75.16	1.13	4.24	7382	13,288
Semibituminous, Paris, Ark.	2.77	14.69	73.47	9.07	2.79	4.02	78.71	1.46	3.95	7652	13,774
Semianthracite, Russellville, Ark.	2.07	9.81	78.82	9.30	1.74	3.62	80.28	1.47	3.59	7612	13,703
Anthracite, Mammoth seam, St. Nicholas, Schuylkill Co., Pa.	2.80	1.16	88.21	7.83	0.80	1.89	84.36	0.63	4.40	7388	13,298

Cannel coal is a type of coal made up almost exclusively of fine particles of vegetable matter, such as spores and seeds. Any rank of coal may show a cannel phase. *Coking coal* includes those coals which, when heated to redness out of contact with the air, form a hard, porous cake, or coke. All coals do not possess this property. *Carbonite* is a natural coke formed where igneous rocks invade coal beds.

Structural features. — Coal beds are commonly interstratified with sandstones and shales (Fig. 72), but in the case of the lower-rank coals the associated rocks are often but slightly consolidated (Fig. 71). Coal beds may vary in their extent and thickness, and are subject to the same disturbances, such as folding (Fig. 73), faulting, and jointing, as other sedimentary rocks. At times they show shale partings which thicken and thin from point to point. One or more separate beds of coal may be present in a formation, but all are not necessarily workable; in fact for coals of the highest heating values beds less than 14 inches thick are not considered workable in the United States, and for lower calorific value they must be correspondingly thicker.

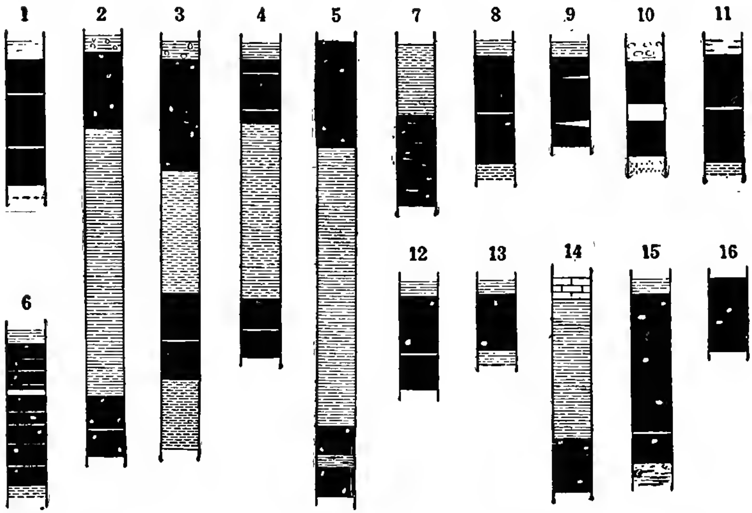

FIG. 72. — Sections of Clarion coal, Foxburg quadrangle, Pa. The coal has two beds with a variable interval of clay, shale or sandstone in between. The lower bed has a persistent "binder" one-quarter to six inches thick near the middle and in places additional binders. Nos. 1, 2, 3, 4, 5 represent both upper and lower Clarion coal, while Nos. 6 to 16 inclusive represent the lower Clarion. (After Shaw and Munn, U. S. Geol. Survey, Bull. 454, 1911.)

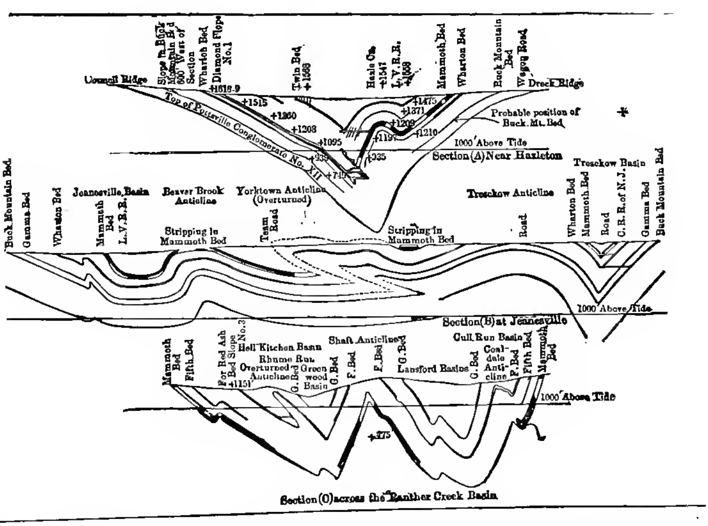

FIG. 73. — Section in coal basins of Pennsylvania, showing several beds in same sections and also intense folding. (From 2d. Penn. Geol. Survey.)

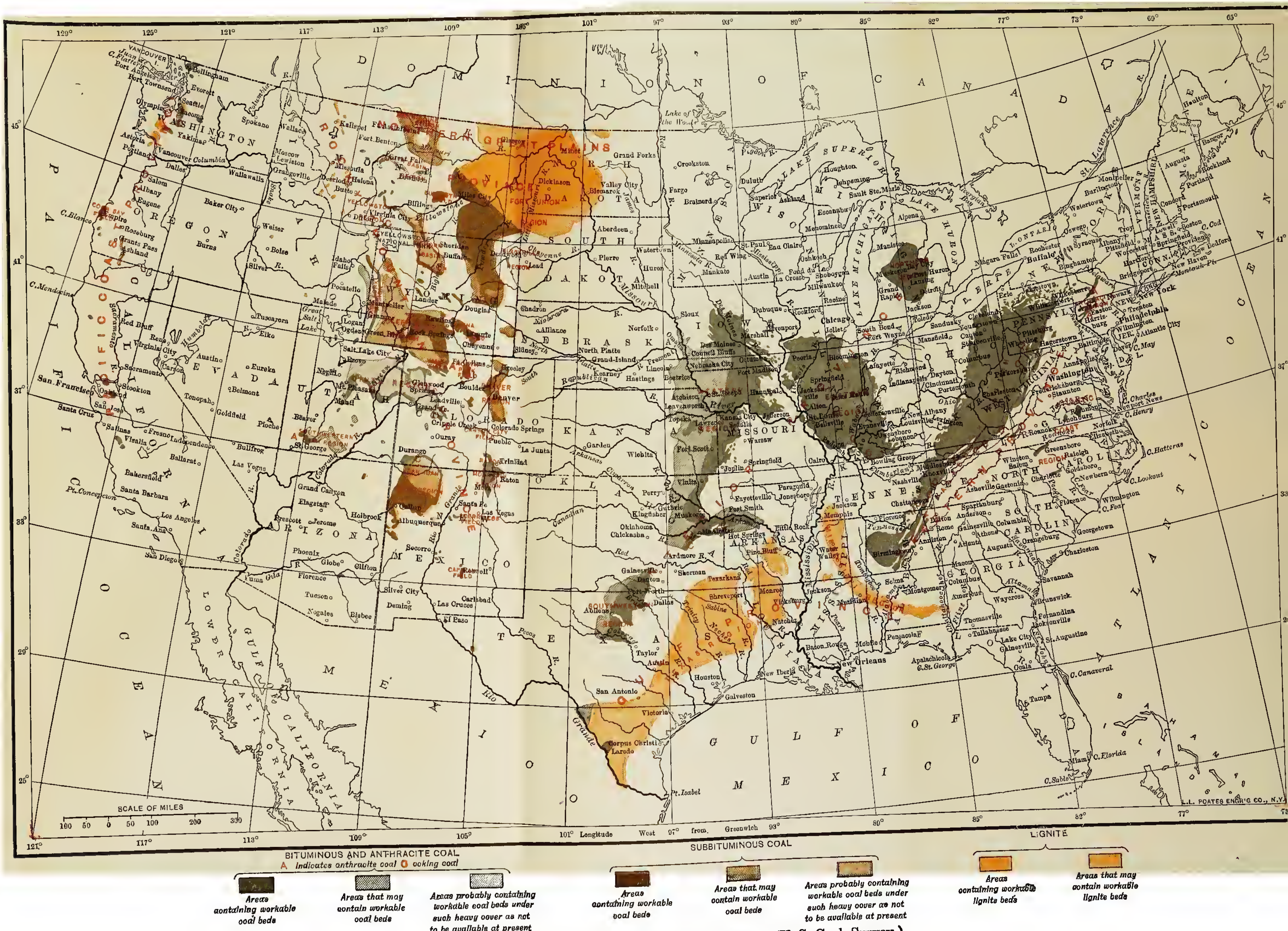

Fig. 74. — Map of coal fields of the United States. (U. S. Geol. Survey.)

Distribution and uses of coal. — Coal deposits are widely distributed in the United States as shown by the map, Fig. 74. The chief use of coal is as a fuel. Peat can be, and is, employed for this purpose, giving the best result in briquetted form, but it is of little commercial use in regions where better coals occur. Lignite, on account of its high moisture content, dries out and disintegrates easily, hence gives better results if fired in a gas producer, or used in briquetted form. Bituminous coal may be used as mined, or for metallurgical purposes, if first converted into coke. It may also be washed before shipment to market. Anthracite is first crushed partly for the purpose of sorting it into different sizes, and partly to facilitate the elimination of associated shale.

The distribution of coal in the United States and by ranks is shown on the map, Fig. 74.

Hydrocarbon-bearing Sediments

Under this heading is included a series of substances, chiefly compounds of carbon and hydrogen (hydrocarbons), with variable amounts of oxygen, sulphur, and nitrogen. They range from gases, through liquids and viscous materials, to solids, the four physical conditions being represented respectively by natural gas, petroleum, mineral tar or maltha, and asphalt. With very few exceptions, all commercially valuable occurrences are found in sedimentary rocks.

Properties of petroleum. — Petroleum is a liquid consisting of a complex mixture of liquid, gaseous, and solid hydrocarbons, and hence varies in its color and density, depending on the nature and relative amounts of the hydrocarbons present. Nitrogen is a minor constituent and sulphur is variable, being abundant only in exceptional cases. The specific gravity of petroleum ranges commonly from about 0.8 to 0.98. Petroleum varies also: (1) in the temperature at which it solidifies, (2) in the minimum temperature at which it gives off inflammable vapors (flashing point), and (3) in the boiling point.

If petroleum is exposed to rising temperature, the lighter oils distill off first, and the heavier ones last, these separates being known as gasoline, benzine, and heavy naphthas, while there is left behind a residue of paraffin or asphalt-like character. Different oils yield different quantities of the several distillates. The calorific power of crude petroleum ranges on the average from 17,000 to 20,000 B.t.u's.

Properties of natural gas. — Natural gas consists chiefly of marsh gas (CH_4); but other hydrocarbons such as ethane (C_2H_6), ethylene (C_2H_4), propane (C_3H_8), etc., as well as other gaseous compounds

may be present. The relative amounts of these affect the heating value of the gas. Natural gas is colorless, odorless, burns often with a luminous flame, and when mixed with air is highly explosive. Exceptionally, it contains a high percentage of nitrogen, and is then of no value.[1]

Occurrence of oil and gas. — Oil and gas are, with few exceptions, always found in sedimentary rocks (Fig. 75). At least a little gas usually occurs with the oil, but the gas is at times alone. A well may yield either one or the other.

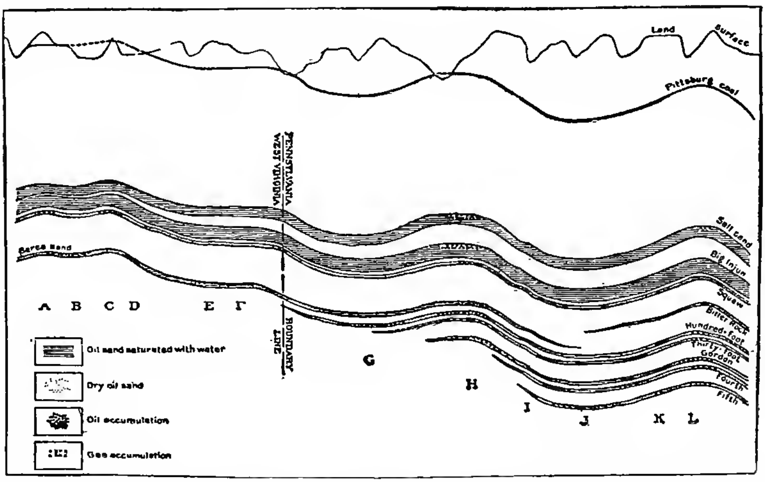

FIG. 75. — Diagrammatic section of sands in the central Appalachian region. (After Griswold and Munn, U. S. Geol. Survey, Bull. 318.)

The two are sometimes found in separate beds, or in different parts of the same bed. In most cases the oil or gas has collected in the pores of the rock, but occasionally they are found in joint planes or other kinds of cavities.

The rock containing the oil or gas is known as the oil or gas rock, or *sand*. It is usually a sandstone of varying coarseness and porosity, and less often a limestone or even shale. That portion of a formation containing the oil or gas is known as a *pool*. A district may contain several pools, and in each one there may be one or more sands lying at different levels (Fig. 75). Indeed, in some districts as many as 10 or 12 sands may be struck in drilling, but all are not necessarily productive in all parts of the area.

[1] Many analyses can be found in the U. S. Geol. Survey, Min. Res., 1911, II, p. 324, 1912.

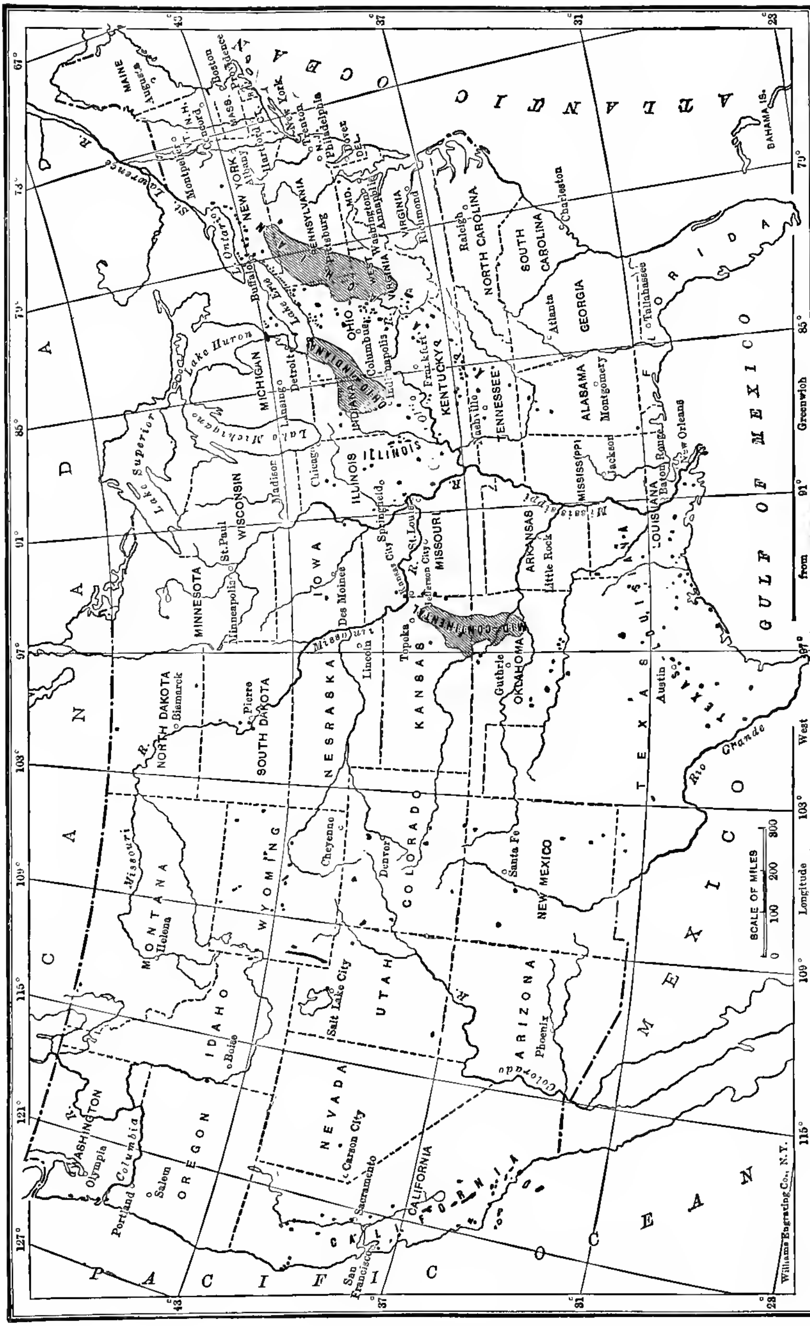

FIG. 76. — Map showing oil and gas fields of the United States. (After Day from Ries' Economic Geology.)

The thickness of the producing rock ("pay sand") will vary in the different fields. In some, the sand is as thin as 2 feet, in others as much as 75 or 100 feet. Its depth below the surface may range from less than 100 to 3000 or 4000 feet. Both oil and gas are usually under pressure in the rocks, several hundred pounds per square inch being not uncommon.

In many fields oil and gas seem to be associated with arch-like structures, such as anticlines or domes, and a knowledge of this fact is made use of in locating oil pools.

Origin of petroleum and natural gas. — It is now generally believed that petroleum and natural gas are derived mostly from plants of low orders, yielding waxy, fatty, gelatinous or resinous products, with which may be mingled more or less animal matter.

These animal and vegetable materials deposited as organic detritus in mud of either fresh or salt water bodies were first attacked by aërobic bacteria, and later subjected to slow deoxidation by anaërobic microbes. Later on when the products of decay were buried they were further altered by dynamo-chemical action, a further devolatilization took place, and as pointed out by White, the progressively more altered shales when distilled yield the oils with the greatest amount of light hydrocarbons.

Distribution and uses of petroleum and natural gas. — Petroleum is utilized for power in gas engines and under boilers; for heat, light, and lubrication. Natural gas is employed for both heating and lighting. Fig. 76 shows their distribution in the United States.

Oil Shales. — These are argillaceous or shaly deposits, containing *kerogen* or bituminous matter, which on destructive distillation, yields oil and tarry matter, as well as ammonia. In the United States they have been found in formations ranging from Devonian to Tertiary in age, but the best and most extensive deposits occur in the Tertiary of Colorado, Utah, Wyoming, and Nevada. A shale to be of value should yield from 30 to 60 gallons of oil per ton, in addition to ammonia. These deposits form a reserve supply for the future.

Solid and semi-solid bitumens. — Under this heading are included (1) bitumens of a more or less solid character, which occupy fissures in rocks, or in rarer cases basin-shaped depressions on the surface; (2) bitumen of viscous character or *maltha*, which oozes from fissures or pores of the rocks and sometimes collects in pools on the surface; and (3) bitumen filling the pores of sedimentary rocks, such as sandstones or limestones.

The first class represents the purest type, that found in veins being used in the manufacture of water-proofing compounds, varnishes, and insulating materials, while the basin type (example Trinidad asphalt)

is employed chiefly for asphalt pavements. The second type is of little economic value. The third class can be used for asphalt pavements, but comes in serious competition with artificial mixtures of crushed stone and Trinidad asphalt, or oil asphalt obtained from distillation of the heavier grades of crude petroleum.

Vein bitumens are found at several localities, but those worked are located chiefly in eastern Utah. No lake asphalt deposits are found in the United States. Bituminous sandstones have been worked in Kentucky, Oklahoma, and California.

METAMORPHIC ROCKS

Introduction. — The term metamorphic, when broadly applied, includes any kind of change or alteration that a rock has undergone. Metamorphism involves changes that are both physical and chemical, and the rock so altered may have been originally of sedimentary or igneous origin.

The alteration (metamorphism) includes change in mineral composition or texture, or both, and is often so complete as to obscure the primary characters of the original rock. It therefore becomes difficult, if not impossible, in many cases, to say with certainty whether the metamorphic product was derived from an original igneous or sedimentary rock. All gradations exist between sedimentary rocks and their metamorphic equivalents on the one hand, and between igneous rocks and their metamorphic products on the other.

As discussed in Chapter III, the alteration of rocks may be a deep-seated change or a superficial one, the resulting products in the two cases being widely different. The alteration of rocks by atmospheric agents, known as *weathering* and therefore superficial, is discussed in Chapter IV, so that what follows here applies to rocks altered only under deep-seated conditions.

Agents of metamorphism. — The principal agents involved in the alteration of igneous and sedimentary rocks and the production of their metamorphic equivalents are: (1) Earth movements and pressure; (2) liquids and gases, chiefly water; and (3) heat. The effect of the first is mechanical; of the second and third, chemical, usually indicated by the production of new minerals. These are discussed in Chapter III.

Chemical composition of metamorphic rocks. — The chemical composition of metamorphic rocks varies greatly, because of the marked differences in composition of the many kinds of igneous and sedimentary rocks yielding, when altered, metamorphic ones. The chemical composition of many rocks is not greatly changed during

the process of metamorphism; hence, metamorphosed sedimentary rocks, with minor modifications, have the chemical composition of muds, grits, sandstones, etc.; while metamorphosed igneous rocks have the composition of granites, diorites, etc.

Mineral composition of metamorphic rocks. — The mineral composition of metamorphic rocks is subject to wide variation. Certain silicate minerals are known to be characteristic of the igneous rocks, while hydrated oxides, carbonates, etc., occur chiefly in sedimentary rocks. Other minerals like quartz, feldspar, mica, etc., are found in both igneous and metamorphic rocks, while chlorite, talc, serpentine, common garnet, etc. are common minerals in metamorphic rocks.

Texture and structure of metamorphic rocks. — The metamorphic rocks being crystalline in texture resemble most the igneous ones. Further resemblance to igneous rocks is shown in many metamorphic ones in the development of *pseudo-porphyritic* texture.

Metamorphism as explained in Chapter III frequently results in the production of a secondary parallel structure in rocks known as *foliation* (rock cleavage) which resembles more or less closely bedding or stratification in sedimentary rocks, and along which the rocks tend to split with more or less ease. Hence metamorphic rocks resemble sedimentary ones in structure, and at times some igneous rocks, for a similar primary structure is often shown in lavas and to some extent in plutonic types.

The foliated structure in metamorphic rocks, due to the parallel arrangement of the minerals, is entirely secondary, and is not connected with bedding in sediments, although the two may coincide at times. The terms bedding and stratification, therefore, should not be applied to foliation in metamorphic rocks.

Varieties of structure. — We may recognize the following three principal structures in metamorphic rocks: (1) *Banded* (Fig. 77), in which lithologically unlike layers of minerals arranged in more or less parallel bands are shown, as in gneisses; (2) *Schistose*, representing the development of a rather evenly foliated structure, as a result of which the rock often splits easily, but not always very regularly, as in schists; and (3) *Slaty* (Fig. 81), in which the mineral grains are very small, and the rock dense, but having the property of splitting (slaty cleavage) into thin, even slabs. Gradations between any two may occur.

Because of the foliated structure of many metamorphic rocks, they tend to split or separate more readily parallel to the foliation planes. This may be an advantage in certain cases, as in the cleaving of slate, but in others it may be a distinct disadvantage in that it may prevent the extraction of thick blocks of stone, or cause the rock to

break off and slide on exposed surfaces of cliffs or in the walls of excavations.

Criteria for distinguishing metamorphosed igneous and sedimentary rocks. — In the study of a metamorphic rock, it is desirable but not always easy, to determine whether the rock was derived from an original igneous or sedimentary one. The evidence upon which the geologist depends is gained partly from field study of the mode of occurrence, general characteristics, and relationships of the rocks, and partly from microscopical and chemical study of rock specimens collected in the field.

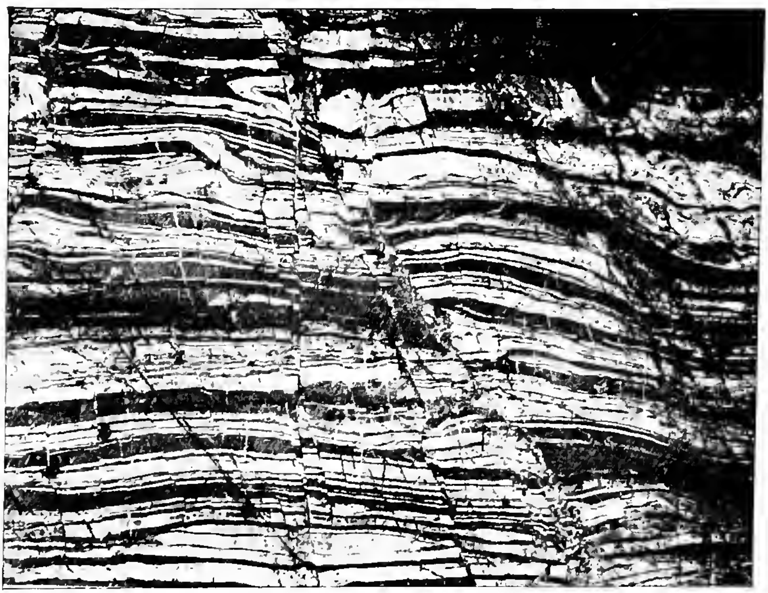

FIG. 77. — Magnetite gneiss, showing distinct banding. The bands are also broken by small faults, Temagami, Ont. (H. Ries, photo.)

In those cases where metamorphism has not been extreme, the textures and structures of the original rocks have not been completely obscured, and the discrimination of the derived rock is not so difficult. In many cases, however, the metamorphism has been so complete as to entirely obliterate all trace of the general character of the original rock, and discrimination becomes extremely difficult. Various criteria have been proposed in such cases, but probably chemical analysis and mineral composition are among the most important.

Classification of Metamorphic Rocks

Since in most cases it is not possible on megascopic grounds to group metamorphic rocks according to origin, whether derived from original sedimentary or original igneous masses, some other basis of classification that is practical must be sought. Probably the classification of metamorphic rocks which best meets the needs of the engineer, and the one followed in this book, is based chiefly on mineral composition, texture, and structure. It follows.

CLASSIFICATION OF METAMORPHIC ROCKS

I. Gneisses of various kinds.
II. Crystalline schists of various kinds.
III. Quartzites.
IV. Slates and phyllites.
V. Crystalline limestones and dolomites (marbles).
VI. Ophicalcites, serpentines and soapstones.

Other kinds of metamorphic rocks are known, but as they are of little or no importance to the engineer, they are not considered. The six groups given above are treated below in the order named.

It is helpful to illustrate in a general way the metamorphic equivalents of the more common types of sedimentary and igneous rocks, as shown in the following tables.[1]

TABLE OF SEDIMENTARY ROCKS AND THEIR METAMORPHOSED EQUIVALENTS

Loose sediments.	Compacted sedimentary rocks.	Metamorphic rocks.
Gravel	Conglomerate	Gneiss and schist
Sand	Sandstone	Quartzite
Silt and clay	Shale	Slate and schist
Lime deposits	Limestone	Marble and schist

TABLE OF IGNEOUS ROCKS AND THEIR METAMORPHIC DERIVATIVES

Igneous rocks.	Metamorphic rocks.
Coarse-grained feldspathic rocks, such as granite, syenite, etc.	Gneiss
Fine-grained feldspathic rocks, such as felsite, tuffs, etc.	Schists, slates, etc.
Ferromagnesian rocks, such as dolerites and basalts	Schists, etc.

[1] Pirsson, Rocks and Rock Minerals, p. 348.

Gneiss. — Gneiss,[1] is used here strictly in the structural sense. It may be defined as any banded metamorphic rock, whether originally of igneous or of sedimentary origin, the bands of which are mineralogically unlike and consist of interlocking mineral particles which, for the most part, are large enough to be visible to the naked eye. The bands may vary in regularity (Figs. 77 and 78), and in thickness may range from a fraction of a centimeter to many centimeters. Likewise a similar range in thickness of the different bands of the same gneiss may be noted.

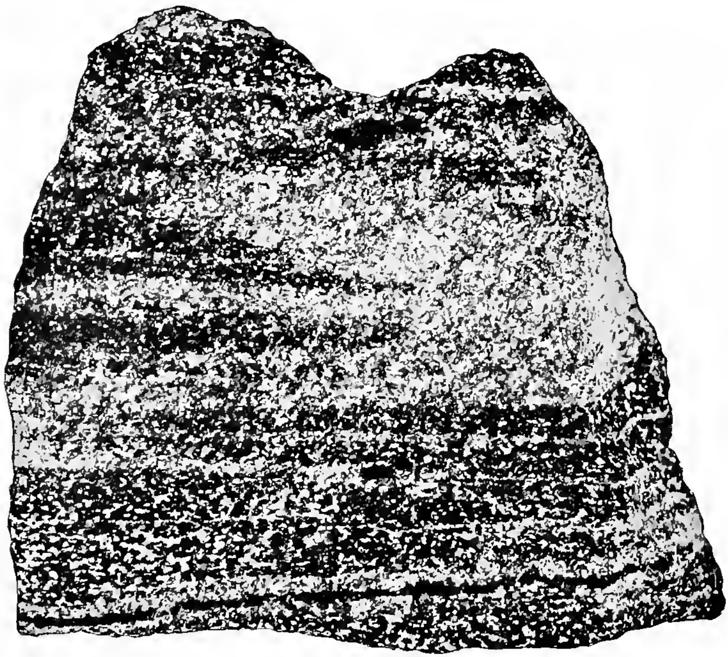

Fig. 78. — Hornblende gneiss, showing irregular banding. Dark patches, hornblende; light areas, mixed quartz and feldspar. (From Ries, Building Stones and Clay Products.)

The most important gneisses correspond in mineral composition to plutonic igneous rocks, but they are not necessarily of igneous origin, since many are known to be metamorphosed sediments. Feldspar, quartz, mica, and hornblende are the commonly occurring minerals in gneiss, but many others may occur.

Varietal distinctions of gneisses may be based on (1) structural differences, such as *banded gneiss*, *foliated* or *lenticular gneiss*, etc.;

[1] Quarrymen usually but erroneously apply the name granite to gneisses.

(2) character of the prevailing accessory mineral, as in granite, such as *biotite gneiss*, *hornblende gneiss*, etc.; and (3) on composition and origin, such as *granite-gneiss*, *diorite-gneiss*, etc.

Gneisses are compact crystalline even-granular rocks in which the principal minerals though variable in size can be distinguished by the naked eye. Porphyritic texture is common among the feldspathic gneisses in which feldspar occurs as the porphyritic mineral. They are banded rocks, in which the lines may be straight or regular, or curved and contorted. The lines may be continuous or short and lenticular, and the individual bands may be extremely thin or thick. Variation in color may range from nearly white through various shades to nearly black. Other physical properties are similar to their equivalent igneous types, and are dependent chiefly on mineral composition, size and shape of grain.

FIG. 79. — Biotite gneiss, showing folding of the bands.

Uses. — On account of the banded structure, gneiss cannot be worked so uniformly as granite, hence its use is more restricted. On the other hand, the banded structure permits of the rock being split into more or less parallel flat surfaces, and of use in the construction of rough walls and for street work. When used for constructional purposes the rock should be placed like sedimentary ones, so that the foliation lies in the mortar bed and not on edge, in order to avoid splitting and scaling.

Gneiss is quarried in many localities in the eastern belt of crystalline rocks but usually for local demands. Those gneisses most widely used

for structural work are granite-gneisses, and are similar to granite in weight per cubic foot, absorption, and crushing strength. Gneiss may also be used for concrete and road material.

Occurrence and distribution. — Gneiss is one of the most common and widely distributed of rocks. It is especially abundant in the older geological formations, forming extensive areas in Canada, the Appalachians, Cordilleran, and upper Great Lakes regions in the United States; and has similar wide distribution over other parts of the world.

Crystalline schists. — Foliated metamorphic rocks, the individual folia being mineralogically alike, and the principal minerals visible to the naked eye. This definition is uniform with that of gneiss and slate, into either of which a schist may grade. Because of this fact, it frequently happens that no hard and fast line can be drawn between schists and gneisses, and by becoming finer in grain and texture, the schists may grade into slates.

Mineralogically the crystalline schists include a large and extremely variable group of rocks. They differ from the gneisses in mineral composition chiefly in the lack of feldspar as an essential mineral, although they may be and are sometimes feldspar-bearing. Quartz is the most frequently occurring essential constituent, with, in the more common varieties, one or more minerals of the mica, chlorite, talc, amphibole, or pyroxene group.

Varietal names based chiefly upon the character of the prevailing ferromagnesian mineral present include *mica schists*, *chlorite schists*, *hornblende schists*, *talc schists*, etc. Of these, the mica schists are the most common and widely distributed. The mica may be biotite or muscovite, or both. *Greenstone schists*, sometimes called "green schists," has been applied to schists of green color rather than to those of definite mineral composition, and both hornblende schists and chlorite schists have been included under it. *Sericite* schists contain the hydrous mica sericite.

All schists are alike in having a more or less pronounced schistose structure along which they split readily, sometimes with smooth and even surfaces, but they break with more or less difficulty, and often with irregular surfaces, at right angles to the schistosity.

In *color*, schists exhibit a very wide range, dependent chiefly upon the kind and proportions of their principal minerals. Mica schists usually vary from very light, through gray and brown, to very dark, depending on the proportion of light- and dark-colored micas present. Chlorite schists are usually some shade of green; common hornblende schists vary from green to black; and talc schists are

usually light, white to pale green, yellowish, or gray; sometimes dark gray.

Uses and applications. — Schists as a rule are undesirable for dimension stone because they split readily, do not cut straight across the foliation planes, and scale off in weathering. When sufficiently solid they are sometimes used for rough construction, as foundation walls. Very fine-grained schists have sometimes been used locally for flagging, or split into thick slabs for roofing.

Schists, on account of their tendency to split off along the foliation planes, are often treacherous if unsupported on steep or vertical faces, where the schistosity is parallel to the surface. On account of the slippery character of the foliation planes, schists will sometimes if unsupported cause rock slips in quarries, railway cuts, and underground workings. In many schists, especially in some of the common mica varieties, quartz is distributed through the rock in the form of eyes or small lenses about which the mica folia are wrapped, so that when parted along the direction of foliation an uneven or lumpy surface is shown. Because of their foliated structure schists are not desirable rocks for use as building stone.

Occurrence and distribution. — The crystalline schists have great areal distribution and are the common types in regionally metamorphosed areas. Mica schists form the country rock over much of the eastern crystalline belt including New England and extending southwestward to middle northern Alabama. They also occur, though to a less extent, around Lake Superior and in the West. Hornblende schists are very common rocks in metamorphic regions, where they form belts, less often independent large areas, in the midst of other metamorphic rocks, especially gneisses and mica schists. Chlorite schists and talc schists are common types in New England, the crystalline region of the Appalachians, and around Lake Superior.

Quartzite. — Quartzites, the metamorphosed equivalents of sandstones and into which they may grade, are hard and compact crystalline rocks which break with a splintery or conchoidal fracture. They differ from sandstones mainly in their greater hardness, denseness, and crystalline character, properties which result from metamorphism. A practical distinction that may often be made between the two rocks is that, when sandstones are fractured, the fracture passes between the individual sand grains and not across them, whereas in quartzites the fracture passes through rather than between the component grains.

Some quartzites are remarkably pure, and are composed almost entirely of quartz, though many contain other minerals besides quartz,

some of which have resulted from the metamorphism of the clay, lime, and iron oxide cement which bound the sand grains together in the original rock. There may be present in addition to quartz, feldspar, mica, chlorite, cyanite, epidote, magnetite, hematite, graphite, and sometimes calcite. One or more of these minerals sometimes occur in such amounts as to exercise some control over the properties of the rock. The chemical composition, therefore, of quartzites will vary in accordance with that of mineral composition.

We may recognize *chloritic quartzite*, *micaceous quartzite*, *feldspathic quartzite*, etc., according to the principal accessory mineral present. *Buhrstone* is a cellular but hard and tough quartzite representing, in some cases at least, a silicified limestone, and formerly used as a millstone. *Quartzite schist* is a variety in which foliated structure has been developed, the surface of the foliation planes being coated with scales of mica. Quartzites which have formed from pebbly sandstones or conglomerates are known as *conglomerate quartzites*. The pebbles in some of these have been stretched and flattened from dynamic metamorphism.

Quartzites are hard and tough, usually firm and compact, granular rocks, whose individual grains may range from fine to coarse in size. They may form thin or thick massive beds in the midst of other metamorphic rocks, especially schists. They may be white, gray, yellowish, greenish, or reddish in *color*. The dense and compact varieties have low porosity and absorption, and high compressive strength. These properties together with that of high siliceous composition render quartzite a resistant and durable rock. They are usually hard to drill and also to dress.

Uses. — On account of their great durability and resistance to atmospheric agents and high temperatures, quartzites, whose joint planes are sufficiently spaced to permit the extraction of dimension stone, may be used to advantage as a building stone. Hardness is their principal drawback, both in quarrying and in dressing the stone, hence they are not much used for structural work. In the form of crushed stone, quartzites are admirably suited for railroad ballast, concrete work, etc. The purer varieties are sometimes ground for glass sand.

Occurrence and distribution. — Quartzites occur in association with schists and other metamorphic rocks in masses up to hundreds of feet in thickness. They are widely distributed rocks, occurring in nearly all areas of metamorphosed sediments, but have their greatest development in the older geological formations. Quartzites are common in the eastern metamorphic region, including New England

and the Appalachians, around Lake Superior, and in many places in the West.

Slate. — A thinly cleavable rock, the cleavage pieces of which are mineralogically alike, and the mineral grains so small in size as not to be distinguishable by the eye. It is a dense, homogeneous rock of very fine-grained texture. The cleavage (Fig. 81) of slate is a secondary structure produced by metamorphism and not an original one in the sense of bedding, stratification, or lamination, as in shales and similar sediments; hence, the distinction between slate and shale.

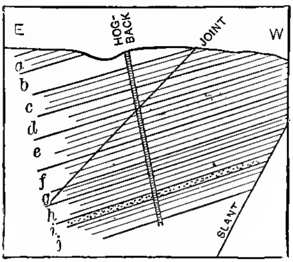

Fig. 80. — Section in slate quarry with cleavage parallel to bedding. *a*, purple slate; *b*, unworked; *c* and *d*, variegated; *e* and *f*, green; *g* and *h*, gray-green; *i*, quartzite; *j*, gray with black patches. (After Dale.)

Slates are the metamorphic equivalents of muds and shales and less often of volcanic ash and tuffs. They represent therefore the finest particles of mineral matter. Shales, slates, phyllites, and mica schists form a continuous series of rocks derived chiefly from clay or mud by progressive metamorphism (dehydration and crystallization). Gradations exist between shales and slates on the one hand, and between slates, phyllites, and mica schists on the other.

Megascopically, the mineral composition of slates is of no importance, since the constituent grains of the rock are too small in size to be distinguished by the eye. When examined in thin section under the microscope, however, the principal minerals are seen to be quartz and mica (biotite and muscovite, including sericite), besides many lesser ones. Pyrite is a constituent of many slates and when present in quantity or in large lumps it renders the slate unmarketable. Magnetite is especially undesirable in slate that is to be used for electrical switchboards.

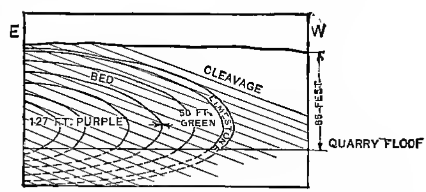

Fig. 81. — Section showing relation of cleavage to stratification. (After Dale.)

Classification of slates. — The following classification of slates has been suggested by Dale.

A. Clay slates. — Purple red of Penrhyn, Wales; black of Martinsburg, W. Va.

B. Mica slates.

1. Fading: (*a*) Carbonaceous or graphitic (blackish); Lehigh & Northampton Counties, Pa.; Benson, Vt. (*b*) Chloritic (greenish); "Sea green," Vermont. (*c*) Hematitic and chloritic (purplish); Purplish of Pawlet and Poultney, Vt.
2. Unfading: (*a*) Graphitic; Peachbottom of Pa. and Md.; Arvonia, Va.; Northfield, Vt.; Brownville, Monson, Me.; North Blanchard, Me.; West Monson, Me. (*b*) Hematitic (reddish); Granville, Hampton, N. Y.; Polk County, Ark. (*c*) Chloritic (greenish); "Unfading green," Vermont. (*d*) Hematitic and chloritic (purplish); Purplish of Fair Haven, Vt.; Thurston, Md.

FIG. 82. — Slate quarry, Penrhyn, Pa. (From Ries' Economic Geology.)

Slates are dense and compact very fine-grained rocks, whose component minerals are not distinguishable megascopically. Their most important structural feature is *cleavage*, by virtue of which the rock readily splits into thin sheets or slabs, and the regularity and perfection of which renders the slate of value for roofing purposes. Slaty cleavage (p. 140) may or may not coincide with the original bedding; usually it does not, but may cut it at almost any angle. The original bedding planes may appear as bands known as *ribbons*, which may be of different color or of different mineral composition, and which are often plicated. When irregular and numerous, ribbons may render the slate worthless.

The cleavage surfaces may be quite lustrous, but are usually dull, and may be very smooth or may show extremely fine plications. Sometimes the cleavage surfaces are spotted, and in some slates are even knotty from the presence of certain minerals. Slate is usually split for commercial purposes (Fig. 83) before the quarry water has dried out of it, otherwise it does not cleave as well.

FIG. 83. — Splitting slate. (H. Ries, photo.)

False cleavage and *slip cleavage* are names applied to minute plications sometimes seen on the cleavage surfaces of slate. They are due to microscopic slips or faults along which the slate may break easily. The *grain* is a direction along which the slate can split, but not as smoothly as along the true cleavage.

Joints are found in all slate quarries and may traverse the rock in all directions. They are occasionally so numerous as to make the slate worthless, and moreover the joint fractures are sometimes filled with calcite or quartz. The cleavage of the slate is often responsible for the rock slips which occur in many excavations made in this kind of rock.

The usual *color* of slate ranges from gray to dark or bluish-black but red, green, and purple shades are also known. The gray and black slates owe their color to the presence of variable amounts of carbonaceous matter; the red and purple ones to iron oxide; and the green ones sometimes to the presence of chlorite. Green slates may be either fading or non-fading. The average specific gravity of slate is about 2.75, but may be affected by the presence of such minerals as magnetite, pyrite, etc. Slates are rather soft rocks and may be readily cut, a property which is of considerable economic importance. The properties of slates that should be tested are cleavability, sonorousness, cross-fracture, toughness as determined by bending under load, abrasive resistance, transverse strength, and corrodibility as shown by any loss of weight when immersed for several days in a weak acid solution.

The following figures give the tests of a standard American slate, the figures being the average of several:

Modulus of rupture, pounds per square inch	9460
Ultimate deflection in inches, supports 22 inches apart	0.212
Specific gravity	2.76
Per cent absorption in 24 hours	0.23
Amount in grams abraded by 50 turns of a small grindstone	0.208
Per cent of weight lost in acid solution in 63 hours	0.383

Occurrence and distribution. — Slates are common rocks in metamorphic areas and have a wide range geologically. They have rather extensive distribution in the Lake Superior region, and in many places in the West, especially along the western slope of the Sierra Nevada Mountains.

The chief slate-producing areas in the United States are in the East, quarries being operated in Maine, Vermont, New York, Pennsylvania, Maryland, Virginia, and Georgia. There is also a limited production from Arkansas and California (Fig. 84).

The waste in slate quarrying is very high, probably never under 60 per cent and often as much as 80 per cent. The utilization of the waste material is still an unsolved problem, although a little is used as road material, and a still smaller quantity is used for paint when ground and mixed with oil. Of the merchantable product the larger portion is used for roofing purposes, but those pieces which cleave in thicker slabs are sawed and rubbed, after which they are sold for stair treads, tubs, sinks, table tops, etc.

Phyllite. — A name given to a group of thinly cleavable, finely crystalline, micaceous rocks intermediate between mica schists and slates, into which they may grade. They probably represent a more advanced stage of metamorphism than slates. Quartz and usually sericite are the principal minerals, but others, such as garnet, pyrite, etc., are frequently present in small amounts. Probably the so-called *hydromica schists,* described by the older geologists in this country, are for the most part phyllite.

Phyllite differs from slate in containing a larger amount of mica which is visible to the naked eye, and in being more brittle but not so tough. It is usually light in color, sometimes nearly pure white, but frequently of various darker shades, even black in some cases. It is apt to be soft and has a rather greasy feel.

Crystalline Limestones and Dolomites (Marbles)

Crystalline limestones and dolomites are the metamorphic equivalents of ordinary limestones and dolomites described on pages 77 to 83, and are known geologically as marbles; but in the trade the term marble is applied to any limestone that will take a polish, whether

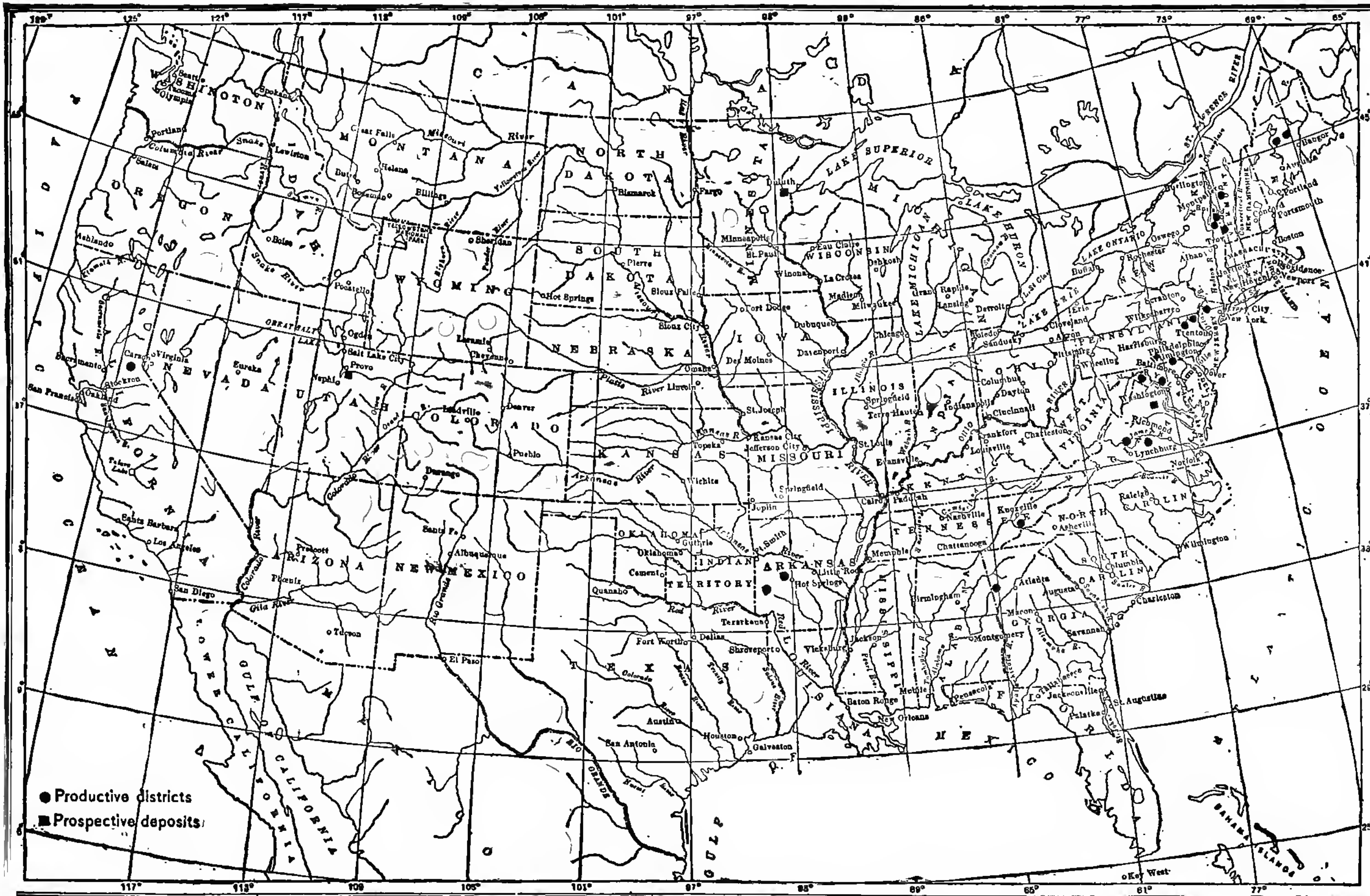

FIG. 84. — Map showing slate-producing districts of the United States. (After Dale, U. S. Geol. Survey, Bull. 275.)

crystalline or not. Most limestones contain impurities, such as silica, carbonaceous matter, iron oxides, argillaceous or clayey material, etc., so that when subjected to metamorphism, the change involves not only crystallization but the development of new minerals. The crystalline limestones and dolomites may show therefore great diversity in mineral composition, ranging from essentially pure crystalline carbonate rocks on the one hand to an aggregate of nearly all silicates on the other.

From carbonaceous material will develop graphite which causes dark spotting or streaking, or in some cases a uniformly dark color. Other impurities of the character mentioned above will develop, under conditions of metamorphism, various silicate minerals, among the more common ones of which are phlogopite and biotite among the *micas*, wollastonite and diopside among the *pyroxenes*, tremolite and actinolite among the *amphiboles*, and grossularite among the *garnets*.

Marbles, when pure, are compact crystalline granular rocks composed of calcite or dolomite, or a mixture of the two. The texture may range from exceedingly fine-grained to very coarse-grained,

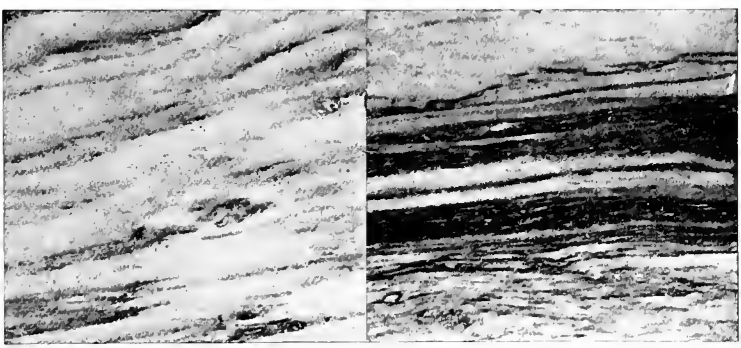

FIG. 85. — Slabs of marble, showing bands and mottlings produced by mica.

with all gradations between these two extremes shown. The texture affects the weathering qualities, ornamental value, and to some extent the working qualities of the stone.

Unlike many metamorphic rocks, marble, when pure, is apt to be massive and without indication of schistose structure, but when impure from the presence of other minerals (such as mica) these may be so arranged as to produce schistosity. This is especially true of the

impure marbles of the Piedmont region in the Atlantic states, where they are frequently found grading into true calcareous schists. Marbles which are strongly banded by mica are not as durable in a severe climate, nor do they take a continuous polish. Some marbles show a brecciated structure (Fig. 54), and though often of highly ornamental character they are not adapted to exterior work. Pyrite and tremolite are sometimes objectionable impurities.

Fig. 86. — Quarry of Vermont Marble Company, Proctor, Vt. (Photo loaned by Vermont Marble Company.)

Marbles snow a wide range of color, dependent chiefly upon their purity. The pure ones are white, others gray to black, and still others may show shades of red, pink, yellow, green, brown, etc. The principal impurities which act as a pigment influencing color are carbonaceous matter and the oxides of iron, as well as finely divided mica. The color may be entirely uniform in the pure marbles, but more often it is spotted, blotched, or streaked (Fig. 85). Absorption is low, usually less than one per cent, but even fine-grained apparently dense marbles may be relatively permeable.[1] The specific gravity

[1] This may be tested by soaking the dry stone for 24 hours in a 4 per cent alcoholic solution of nigrosine, then splitting the marble, and noting how deep the dye has penetrated.

generally averages between 2.66 and 2.79. The crushing strength of a series tested ranged from 11,000 to 19,000 pounds per square inch. The abrasive resistance of the different kinds varies considerably, a fact that is often noticed when they are placed side by side in the same floor. The hardness of the calcite marbles is 3, and of the dolomitic ones 3.5 to 4, but all are readily scratched by the knife. The calcite marbles may be distinguished from the dolomitic ones by effervescing in cold dilute acid (see pages 20 and 21).

Alteration. — Marbles like ordinary limestones are soluble rocks and weather with comparative readiness, the calcareous material being dissolved and removed in solution with such insoluble impurities in the rock left in place to form the mantle of residual material. In many quarries solution fissures penetrate the stone to some depth, causing waste in quarrying. They may also serve as entrance channels for surface waters to reach mine workings or tunnels. Sometimes the coarser textured marbles, especially those of dolomitic composition, weather through physical causes, breaking down into a coarse sand or gravel as in the Adirondacks and western New England.

Occurrence and distribution. — The crystalline limestones are found in metamorphic regions in association with gneisses, schists, slates, etc. with which they form interstratified masses or lenses of variable size. On account of the variation in texture and purity of the different beds in a given section, all may not be of equal commercial value. They have extensive development and economic importance throughout the metamorphic crystalline region of the eastern United States, where quarries have been opened in most of the states, with Vermont, Tennessee, Georgia, Alabama, Massachusetts, Pennsylvania, and New York, in the order named as the principal producers. White marbles are obtained in Vermont, Georgia, and Alabama especially; pink and brown ones from Tennessee, and variegated ones from Vermont and New York. Vermont and Georgia yield gray ones. Marbles are found in places in the West, being developed in Colorado, California, and Washington. They have also been extensively worked in eastern Canada, and in similar metamorphic regions of other countries.

Marbles can be employed for the same purposes as limestones. They are used for dimension stone, but are specially valuable for ornamental and statuary (when white) work. Polished slabs, often of great beauty, are used for wainscoting and flooring.

Ophicalcite, Serpentine, and Soapstone

In general characters and origin this group of rocks has many points of resemblance, and for convenience may therefore be treated together. It is a series whose members range in mineral composition from a mixture of silicate and carbonate minerals as in ophicalcite to essentially all silicate minerals as in the pure serpentine and soapstone. Through ophicalcite, the group may be considered as related to the preceding group of marbles including crystalline limestones and dolomites. In composition soapstone is closely related to talc schist into which it may grade through the development of foliated structure by dynamic metamorphism.

Ophicalcite. — *Ophicalcite* includes marbles (crystalline limestones) that are streaked and spotted with serpentine. The name is usually restricted to a mixture of green serpentine and white calcite, magnesite, or dolomite in variable proportions. The serpentine forms irregular large and small stringers and masses, and may contain unaltered remnants of the original silicate mineral from which it was derived. *Verde antique* is a general name applied to green serpentinous marble.

Ophicalcites were probably derived from originally impure limestones by metamorphism, and the silicate minerals formed were later secondarily converted by hydration into serpentine.

They are not very abundant rocks but are used as a decorative stone. They are soft rocks and can be easily polished, but as a rule they weather readily and unequally on exposure. Another defect in the rock is the presence of numerous joints and fractures so closely spaced that stone of more than a few feet in size can rarely be obtained.

Ophicalcite occurs in Quebec, Canada, in the northern Green Mountains, and in the Adirondacks of New York State.

Serpentine. — Rock serpentine is usually more or less impure from varying quantities of other minerals mixed with it, such as, olivine, pyroxene, hornblende, magnetite, chromite, pyrite, and the carbonates of lime and magnesia, etc. Some of the associated minerals such as olivine, pyroxene, and hornblende are the remnants of original magnesian silicates from which the serpentine was derived. Others, like serpentine itself, are secondary, having formed during the process of alteration.

When reasonably pure, rock serpentine is compact, though a variety of texture may be shown. It is dull to waxy in luster, breaks usually with a smooth to splintery fracture, and is soft enough to be cut by the knife, but from the presence of silica it may be much harder. The usual color is green to yellowish green, sometimes yel-

low, with the more impure forms exhibiting various shades of brown, red, and black.

The serpentine rocks are secondary, and have probably been formed by the alteration of such basic igneous rocks as peridotites, pyroxenites, etc. Although serpentine is a widely distributed rock in metamorphic regions, it seldom forms large bodies, but occurs in places in the metamorphic crystalline region of the eastern United States, in several of the western states, and in eastern Canada. Many serpentine deposits show an abundance of slipping planes, which cause trouble by rock slides or slips in quarries, railroad cuts, and other excavations. Indeed engineers in laying out a railroad may try to avoid this kind of rock if they are familiar with its characteristics.

Serpentine is used chiefly as an ornamental stone, but as a rule is of such low weathering resistance as to often make it unsatisfactory for exterior use. It is quarried to a limited extent at several localities in the United States but most of that employed for decorative purposes is obtained from Greece.

Soapstone. — Soapstone, called also steatite, is composed essentially of the mineral talc, and is closely related to the talc schists into which it grades on the development of foliated structure by dynamic metamorphism.

It usually contains varying quantities of the minerals, mica, chlorite, amphibole (tremolite), pyroxene (enstatite), together with quartz, magnetite, pyrrhotite, and pyrite. Carbonates may be present in some cases.

Soapstone is a massive rock of bluish-gray to green color, sometimes dark, and is soft enough to be readily cut with the knife, hence it can be easily worked. It has a greasy feel, and resists to a marked degree heat and the action of acids, properties which make the stone of especial value for use in the trades, and for which it is extensively quarried. It is found in metamorphic regions in association with talcose and chloritic rocks, sometimes with serpentine and beds of crystalline limestones, and is a common rock in many localities in the metamorphic region of the eastern United States, but Virginia is the chief source of the domestic supply.

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For technologic reports see United States Bureau of Mines and Canadian Department Interior, Mines Branch.

CHAPTER III

STRUCTURAL FEATURES AND METAMORPHISM

Introductory

It is a matter of common observation that the rocks over many regions of the earth have been considerably disturbed since the time of their formation. In some cases this has simply involved a change in position of extensive rock masses, without seriously affecting their structure, as when the sea bottom with its sediments was uplifted without warping; but in other cases the rocks, as a result of stresses to which they have been subjected, incident to movements of the earth's crust, have been more or less seriously disturbed, and their structure more or less changed. We thus find that rocks are bent or folded to a variable degree, and usually traversed by fractures, along which displacement may have taken place.

The chief structures produced then as a result of such disturbances are *folds, joints, faults,* and *cleavage.*

Folds

Introduction. — Beds of sedimentary rock are usually laid down in horizontal position, but departure from this attitude is sometimes noted, especially where deposition takes place on steeply sloping shores and in deltas. Examination of the beds over wide regions of the earth's surface reveals the fact that they no longer preserve a horizontal attitude, but show all degrees of inclination to the plane of the horizon, because of the folding which they have undergone. This is notably the case in mountain regions (Fig. 88). The modification of the original attitude of the beds, referred to as *deformation of strata,* has resulted from earth movements, and is recorded from field study in terms of dip and strike.

Outcrop. — Over wide regions of the earth's surface the solid rock, known as *bed rock,* is covered with a mantle of loose rock, the product of atmospheric agents. Within such regions the bed rock projects in places through the overlying mantle of unconsolidated rock, or in steep erosion slopes along streams, and on high steep slopes of mountains. Exposures of bed rock at the surface are known as *outcrops,* and by their careful field study, including dip and strike, the geologic

structure of a region is determined. The most likely places to search for exposures of bed rock are on steep slopes and hilltops, in stream beds and roads, in cliffs along the shore, and in artificial excavations, including railroads. In the examination of outcrops one must be sure that the bed rock is in place and does not represent a detached mass removed from its original position and which may be partly buried in the mantle rock. Precaution is especially necessary in glaciated regions where large partly buried boulders might readily be mistaken for bed rock in place.

Dip. — By *dip* is meant the angle of inclination of the beds with a horizontal plane (Fig. 87). It is measured in degrees by an instrument known as a *clinometer*, which consists of a pendulum with a graduated arc. For convenience the clinometer is usually combined with the compass, so that from the former the amount of dip may be ascertained, and from the latter the direction. In measuring dip, the direction as well as the amount of inclination is taken. Thus, 24° S. 30° E. expresses the exact position of the particular bed. The maximum angle of inclination of the bed is always taken as the dip.

Strike. — This is the direction of the line of intersection of the dipping bed with a horizontal plane, and is necessarily measured at right angles to the dip (Fig. 87). Like dip, the direction of strike is read with the compass from the north point; thus, N. 60° W. If the direction of the dip remains constant, the strike is a straight line, but with change in direction of dip there also follows change of strike. Since, therefore, the direction of strike is always at right angles to that of dip, if the direction and angle of the latter are measured it is unnecessary to record that of strike. Thus, a bed with an east dip has a north and south strike. Beds having the same strike might show different angles of dip. By accurate measurement and correlation of dip and strike observations on outcrops in regions that have suffered considerable erosion, folds may usually be determined.

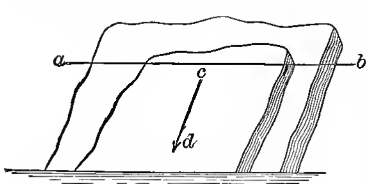


FIG. 87. — Diagram showing dip (*cd*) and strike (*ab*).

Parts of folds. — The line of prolongation of a fold is its *axis*, which may be miles long or only a small fraction of a mile, but whether long or short, the dip decreases and the fold finally dies away. The crest or the trough line is usually not horizontal, but inclined at varying angles with the plane of the horizon, the angle of inclination being defined as the *pitch* of the fold. The plane which bisects the angle between the limbs of a fold is known as the *axial plane* (Fig. 89), and

may be curved from complex movements. The axial plane divides the fold into two parts known as *limbs*.

Principal kinds of folds. — All folds may be regarded as modifications of three principal types, the *anticline*, the *syncline*, and the *monocline*. Anticlines and synclines may be *simple*, *composite*, or *complex*, but as they occur in nature most of them are complex, since they are usually cross-folded, by which is meant their axial lines are folded. A single fold without crenulations may sometimes occur when it is described as a *simple* fold. If crenulations (smaller anticlines and synclines) are superposed on a simple fold it is said to be *composite*. A fold is *complex* when it is cross-folded, that is when its axis is folded.

FIG. 88. — Folded quartzite, Eagle Mountain, Botetourt Co., Va. (Va. Geol. Survey, Bull. II–A.)

Anticlines. — These are folds produced by the arching of beds, so that the limbs dip away from the crest on the two sides of the axial plane (Fig. 89). The arch may be broad or gentle, or sharp and angular with steep dips, all gradations between the two being observed.

Synclines. — These are folds produced by the beds being bent in a downward flexure, so that they dip from both sides towards the

bottom of the trough (Fig. 89). They vary in the same manner as anticlines.

A single or isolated fold sometimes occurs (as in some West Virginia oil districts), but as a rule the area of disturbed strata will show

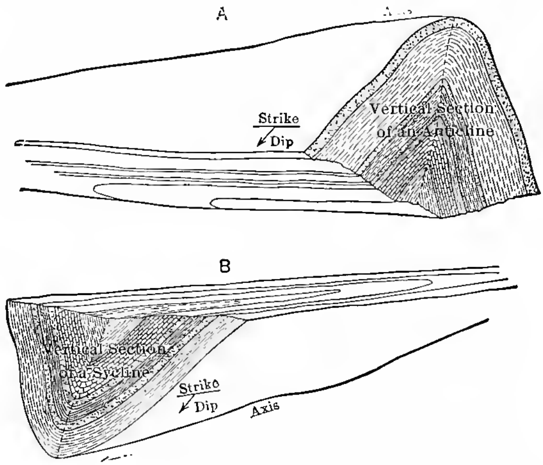


FIG. 89. — *A*, anticlinal fold; *B*, synclinal fold. (Modified from Willis.)

a group of connecting anticlines and synclines, which are either broad and open, or narrow and compressed. In the latter case the beds are often twisted and contorted in the most complex manner. The Appalachian Mountains of the eastern United States form a typical example of this type of structure (Fig. 90).

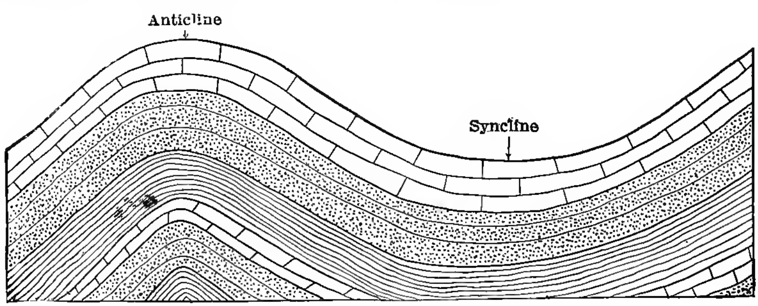


FIG. 90. — Section showing anticline and syncline.

Monocline. — A *monoclinal* fold is a single bend or curvature in strata which lie at different levels on opposite sides of the bend, but have the same general direction of dip (Fig. 92). It is the simplest kind of flexure, and is generally observed in regions of horizontal or

gently dipping beds. Folds of the monoclinal type are developed on a large scale in the high plateau region of the West, and the gently dipping beds of the Coastal Plain province in the eastern United States furnish a good illustration of the monoclinal attitude of strata.

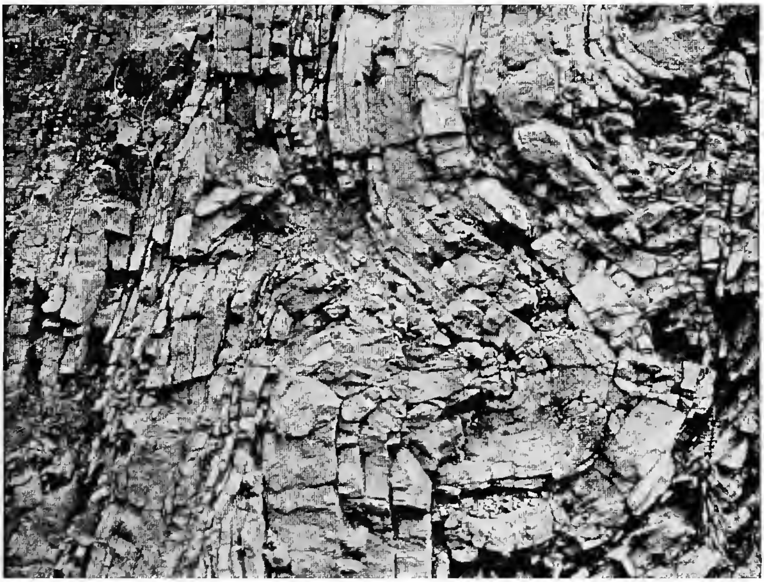


Fig. 91. — Contorted strata in Chickamauga limestone near Ben Hur, Va. (Va. Geol. Survey, Bull. II–A.)

Other types of folds. — The *dome* fold (quaquaversal) is a special case of the anticline, in which the beds dip outward in all directions from a central point (Fig. 94).

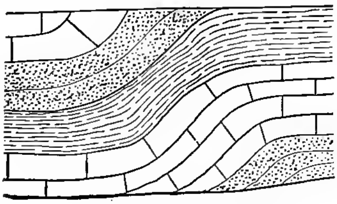


Fig. 92. — Monoclinal fold.

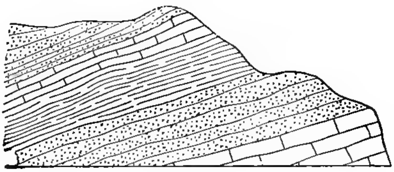


Fig. 93. — Section and block showing monoclinal attitude of beds.

The *basin* fold (centrocline) is a special case of a syncline, in which the beds dip inward from all sides towards a central point (Fig. 95).

Folds of the dome and basin types are regarded as modifications of normal anticlines and synclines, and are not very common structural forms.

When the disturbed beds over any considerable area have been raised into a broad arch composed of minor folds, such a complex of folds is known as an *anticlinorium* (Fig. 96). Conversely, when the beds have been depressed into a broad trough composed of subordinate folds, it is termed a *synclinorium* (Fig. 97). In

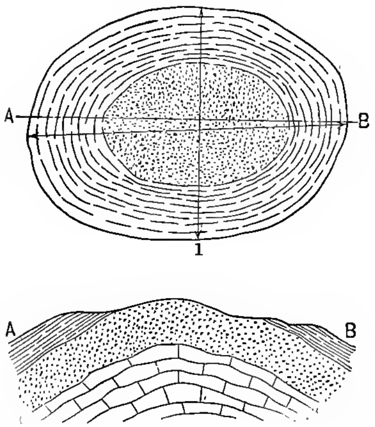


FIG. 94. — Plan and section of dome fold.

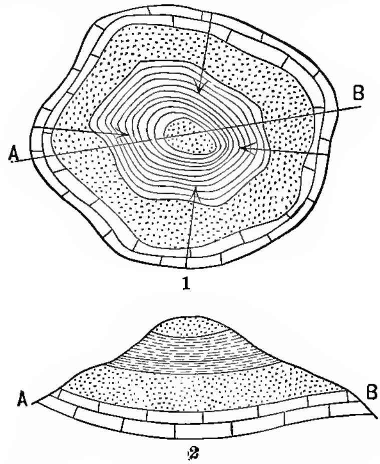


FIG. 95. — Plan and section of basin fold.

other words, the terms *anticlinorium* and *synclinorium* refer to composite arches and troughs, to which, when simple, Dana has applied the terms *geanticline* and *geosyncline*.

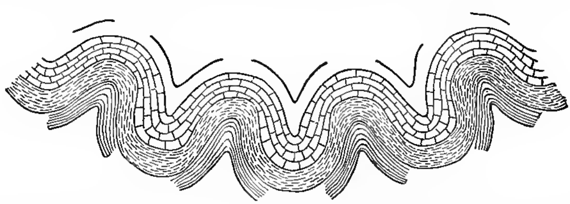


FIG. 96. — Ideal section of an upright normal anticlinorium. (After Van Hise.)

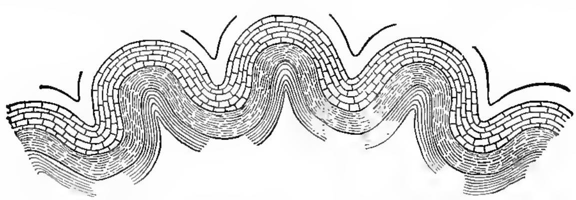


FIG. 97. — Ideal section of an upright normal synclinorium. (After Van Hise.)

Folds whose beds have been so compressed that the limbs are parallel are known as *isoclines* (equal inclination) (Fig. 98, *A–C*). When eroded to a general level the beds of isoclinal folds present a continuous and uniform dip, so that they appear as a single succession of inclined beds, and may be difficult of interpretation. In a

region of such folded and eroded rocks the same bed may be repeated many times at the surface, and unless carefully studied the observer may readily be deceived in the number of independent beds.

Minor folds are frequently developed in weak beds like slate and shale by shearing between two more competent beds like quartzite. Such folds are the result of differential movement between the two competent beds, and are known as *drag folds*.

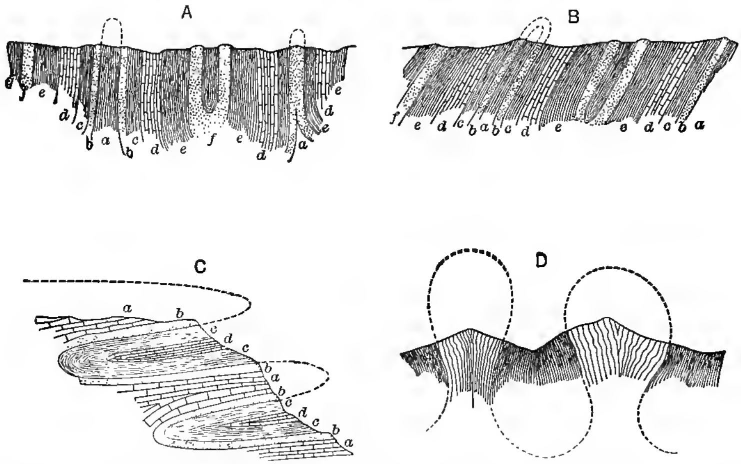


FIG. 98. — (*A*) Isoclinal folds, upright; (*B*) isoclinal folds, inclined; (*C*) isoclinal folds, recumbent; (*D*) fan structure, upright. (Willis.)

Other features of folds. — The principal kinds of folds considered above may be classified (1) with reference to the relation of the limbs to each other, and (2) the amount of compression they have suffered. According to the first principle, each kind of fold may be *upright* or *symmetrical* (Fig. 90), *inclined* or *asymmetrical, overturned* or *recumbent* (Fig. 98), dependent upon the position of the axial plane, whether vertical, inclined, overturned, or recumbent. According to the degree of compression to which the folds have been subjected, we may group them into (1) *open folds* whose limbs are widely spaced, in which the amount of compression has been moderate, resulting in the production of somewhat gentle flexures; and (2) *close folds* whose limbs are in contact (Fig. 98, *A* and *B*), characterized usually by sharp flexures with steep slopes, resulting from a high degree of compression.

Folds modified by erosion. — Folds are rarely found in nature with their original forms, but are modified by erosion (Fig. 101). As soon as they are lifted above sea level, they become, by reason of their position, subject to more rapid erosion than the surrounding areas.

The erosion of folded rocks develops characteristic topographic features. In large folds composed of beds of different degrees of resistance to erosion, the hard beds stand up as ridges and the weak ones mark the position of valleys. Further modification of the sur-

face results from prolonged erosion. Ordinarily anticlines are eroded more rapidly than synclines which seem to offer greater resistance to erosion. Hence in folded strata that have been exposed to erosion for a long period of time, the greatly eroded anticlines form the lower belts or areas, and the more resistant synclines the higher ones.

FIG. 99. — Stretch thrust developed from an overturned fold by stretching of the middle limb. (Heim.)

In some areas of folded rocks that are of great geologic age, such as the Piedmont region of the eastern United States, the folds have been completely truncated by erosion and the surface everywhere reduced approximately to a common general level. In such regions the de-

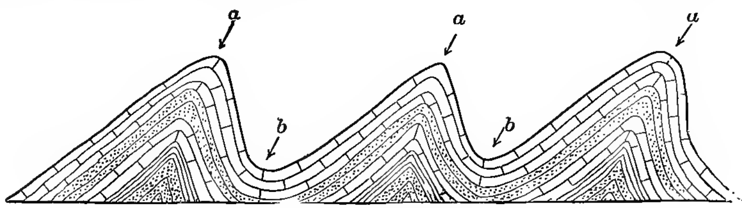


FIG. 100. — Tilted folds.

termination of folded structure cannot be based on topography, but is determined by careful records made of dips and strikes in field study.

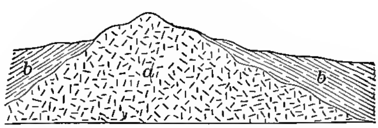


FIG. 101. — Eroded fold, showing igneous rock (*a*), and shales (*b*).

Folding in Relation to Engineering Operations

Tunneling. — Folded rocks sometimes show considerable fracturing along the axis of the fold. In the case of an anticline these fractures diverge upward (Fig. 102), while in a syncline they diverge downward. Where a tunnel is driven along the crest of a fold (Fig. 103), much trouble may be experienced from shattered rock, and it may be necessary to line it from end to end. In the case of a syncline additional trouble may be caused, even with moderate fracturing, because the blocks bounded by fracture planes are like inverted keystones, and are liable to drop out.

The fractures along the crest of a fold may cause additional trouble by serving as channel ways for surface waters.

In driving tunnels in areas of folded rocks the engineer should give careful attention to the geologic structure, since neglect to do so has sometimes led to costly mistakes. Take as an illustration the case of

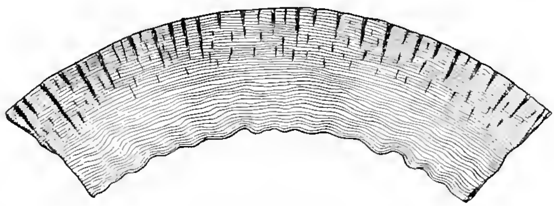


FIG. 102. — Ideal section of bent rock strata showing fracturing along convex surface and compression along concave surface. (After Van Hise, U. S. Geol. Survey, 16th Ann. Rept.)

a tunnel to be driven through horizontal or undisturbed rocks. In this case the structural relations are such that the kind of rock to be removed would be the same throughout the length of the tunnel, unless the section were penetrated by intrusive igneous rocks. If, however, the rocks are folded the problem is different. It then becomes necessary to work out the geologic structure and the kind of rocks to be penetrated, so as to calculate approximately the yardage of each kind of rock to be removed. An anticlinal ridge might appear on rapid inspection to be composed of but one kind of rock, whereas the central portion of the arch might be rock of a totally different nature, firmer or looser, than the outer shell. Indeed large anticlines may be composed not of a single type of rock but of several kinds.

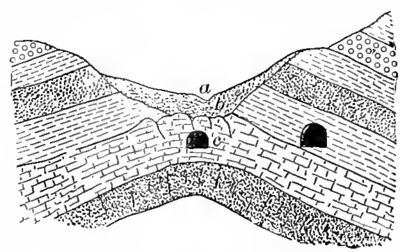


FIG. 103. — Section showing relation of tunnel to anticlinal fold.

Quarrying. — The position of folded beds likewise affects quarrying operations, especially in sandstones, limestones, and marbles, the more so if the beds differ in quality, texture, and color. With uniform beds the attitude is not a matter of such importance, although even in this case it may be desirable to make the quarry floor slanting as it facilitates the extraction of rectangular blocks, since the joint planes are usually at right angles to the bedding planes.

If the beds dip into a hill, the overburden will increase with the

distance from the outcrop, even though the hill surface itself does not rise; but should the dip rise with the hill, the thickness of the overburden does not necessarily increase.

Moderately tilted beds can be worked along the strike as long shallow quarries, and with very steep dip it is often possible to work the quarry as a steep-walled cut, removing the desired beds and leaving the worthless ones standing. This is done in some marble, natural cement rock, and clay-shale deposits. In some marble quarries and even slate deposits the desired bed can be worked by underground methods, as the market value of the stone warrants.

With intense folding the rock may also be so fractured that the deposit contains few or no large blocks.

Ore deposits. — The crushed rocks along the crests of folds sometimes play an important rôle in the formation of ore deposits, since the cavities between the crushed fragments may serve as spaces for the deposition of ore. (Lead and zinc ores of southwest Virginia.)

Mining. — The position of folded beds may influence the method of mining to be employed, as in the anthracite region of Pennsylvania. Intense folding may also shatter the rocks to such an extent as to make the roof unsafe, and require much timbering.

JOINTS

Introduction. — All hard and firm rocks, regardless of kind, are traversed by fractures called *joints*. These may be observed in almost any natural or artificial exposure of hard rock, and constitute division planes which separate the rock into large and small blocks of regular or irregular shape. Jointed structure is of importance in many ways because of its relation to quarrying and general engineering operations, especially tunneling and mining. Joints are also of great importance in promoting rock weathering (p. 157), in the circulation of ground water (p. 214), in the formation of mineral veins (p. 124), etc.

General features. — Joints traverse the rocks in different directions and at various angles, and in most areas at least two systems are observed (Fig. 104). The fractures of each system have the same general direction. In regions of great disturbance three or more sets of joints are not uncommon. The spacing of joints of a single set may vary, being measurable at times in yards, at others in inches, and is a matter of practical importance, since the spacing of joints governs the size of dimension blocks that can be extracted.

Joints may be either vertical (Fig. 104) or horizontal (Fig. 105), and even intermediate positions are not uncommon. In igneous

rocks, horizontal joints are sometimes mistaken for stratification planes. Joints are usually best observed on vertical surfaces, for on horizontal ones the overlying mantle of residual clay or other unconsolidated material may conceal them.

FIG. 104. — Limestone showing horizontal bedding, and one set of vertical joints. The flat face of the quarry is a joint surface of a second set. Cement rock quarry, Milwaukee, Wis. (H. Ries, photo.)

Some joints are closed, others are open, and in rocks like limestone they may be widened by solution. In such cases they become less conspicuous when followed downward. In many quarries much stone bordering the joints has to be rejected at times because of its unsound or weathered character. Closed joints, known also as *cutters*, *closed seams*, and *blind seams*, may cause much waste in quarries.

The following structures, strictly speaking, are not joints, yet they are somewhat associated with jointing: *Rift*, the direction of easiest splitting. In sandstones, for example, it is usually parallel to the bedding, but is not always well developed. *Grain* or *run*, a direction of easy splitting, less pronounced than the rift. *Hardway* or *head grain*, a direction at right angles to both rift and grain.

Classification of Joints. — Joints may be classified as *tension* and *compression joints* to indicate their relation to stresses, whether formed by tension or compression. In folded rocks, joints are grouped into *strike joints* and *dip joints* to indicate their parallelism, or nearly so, in direction to the strike and dip of beds. Again joints are known as *major* or *master joints* when of persistent development, and as *minor joints* when of short extent.

Joints in sedimentary rocks. — There are usually developed in bedded rocks two systems of joints intersecting each other at ap-

proximately right angles, and perpendicular to the bedding planes (Fig. 104). These are the major joints. There may be three or more systems of joints developed. They may be of slight development and confined to individual beds, or they may be extensive and traverse a series of beds of considerable thickness. They frequently end at the contact of two unlike rocks; thus joints which traverse limestone or sandstone may end where shale begins.

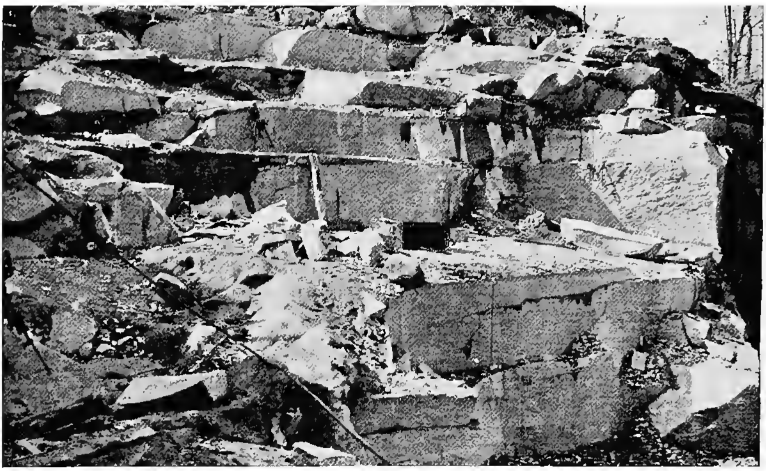


FIG. 105. — Granite quarry, near Woodstock, Md., showing horizontal joints. (T. L. Watson, photo.)

Joints in fine-grained rocks like some hard shales are apt to be more perfect than in coarse-grained rocks like some sandstones. In strongly folded rocks joints are more numerous and more closely spaced than in less disturbed rocks. In flat beds joints are commonly perpendicular to the bedding, and hence vertical. In steeply dipping beds, the joints meet the beds at oblique angles.

Joints in igneous rocks. — Joints in igneous rocks are usually less regular than those in sedimentary rocks, and their arrangement at times is very irregular. In igneous rocks like granite, which have extensive use as building stone, two systems of joints, a vertical set and a horizontal set (Fig. 105) and, in many places, a third or diagonal set, are developed. These may be widely or closely spaced. In some granites the fractures are so closely spaced that dimension stone cannot be extracted, but the rock breaks into numerous small blocks when quarried. Considerable variation is noted in the development of the vertical joints, which are conspicuous in most cases, but may be few and scarcely visible in others.

Horizontal joints which divide the rock into sheets are frequently

strongly developed in granite, and are usually parallel to the rock surface. As a result the sheet jointing is so well developed in some granites that it closely resembles stratification in sedimentary rocks. In flat surface exposures the joints approach a horizontal position; in gently arched exposures they have approximately the same degree of curvature as that of the rock surface; and in steep domes they are correspondingly steep, observing parallelism with the doming surface. They are usually more conspicuous at and near the surface, and become less prominent with depth. Ordinarily they separate the rock into thinner sheets at or near the surface, and into thicker sheets at greater depth. (Fig. 105.)

In dense and compact igneous rocks like basalt, which occur in dikes and lava flows (sheets), there is often developed a regular form of prismatic jointing known as *columnar structure*, as shown in Fig. 49. The columns may be vertical or horizontal, sometimes bent and curved, and may vary greatly in size (length and diameter). They are perpendicular to the principal cooling surface, so that in lava flows and horizontal intruded sheets they are vertical, while in dikes they are apt to be horizontal. The joints in igneous rocks, especially columnar ones, are due chiefly to contraction of the cooling magma, and are tension fractures.

Jointing in metamorphic rocks. — Because of the conditions under which they are formed, metamorphic rocks usually show much jointing, which, as a rule, is less perfect than in sedimentary rocks. In the more massive types of metamorphic rocks like gneiss the jointing resembles that in granite, while in the thinly foliated or schistose types like slate it more clearly resembles that of sedimentary rocks.

Joints in Relation to Engineering Work

Few perhaps realize the important bearing which joints nave on engineering problems, hence their relation to some of the more important ones is briefly discussed.

Quarrying operations. — Joints facilitate the extraction of stone, and the expense of quarrying hard ones like granite would be considerably increased were it not for their presence. While of benefit on the one hand, joints will on the other serve to limit the size of the dimension blocks that can be extracted. An otherwise good stone may be so broken up by jointing, as to be useless for any purpose except road material and the various forms of crushed stone. Joints also permit the entrance of surface water, which in some cases causes more or less weathering of the rock along them, and may furthermore deflect the drill in drilling operations.

A quarry face should be parallel, or at right angles to the joint planes, in order to avoid waste, for if it crosses the joints obliquely, some of the rock will break out in triangular blocks.

Rock slides. — In unsupported rock masses, outcropping on hill-sides, or exposed in the sides of quarries or underground workings, the joints sometimes act as slipping planes, causing slides. If the water gets into the joint cracks and freezes the action is sometimes hastened.

Reservoir construction. — Since joints serve as water passages, engineers constructing dams or reservoirs should see that where the masonry work joins the rock, the joints are not sufficiently numerous to permit leakage. Grouting is sometimes necessary to close them up. Very often the joints are more numerous and open close to the surface than they are at greater depth. The danger here mentioned becomes most serious in limestone formations (Chapter IV).

FIG. 106. — Faulted pegmatite dike in granite, near Boulder, Colo. (H. Ries, photo.)

Water supply. — In regions of igneous and metamorphic rocks that are usually dense and therefore have a minimum of pore space, the supply of underground water must collect almost exclusively in joint fissures, which often form easy channel ways for circulation. But even here there are limitations as to depth at which we may obtain a reasonable water supply (Chapter VI). For example, it has been shown in the Piedmont region of crystalline rocks that the conditions favorable to a water supply lessen rapidly below 250 or 300 feet, for the reason that the joints above this depth are more open.

Ore deposits. — Because joints sometimes serve as channels for underground waters they are at times of importance as structures

(spaces) for the deposition of mineral matter and the formation of mineral veins. Recognition of this occasional relation of ore veins to joints has in some instances facilitated the development of the ore, or search for further ore bodies in those districts where it applies.

Faults

Definition. — A *fault* may be defined as a fracture in the rocks along which displacement of one side with respect to the other has taken place, parallel to the fracture (Figs. 106 and 107). The amount of displacement may vary from a few inches to many thousand feet, and the duration of movement may have been short, or long.

Significance. — Faults are not restricted to any group or kind of rocks, but may traverse all, and are structures of fundamental importance in all regions where they occur. They may, and sometimes do, greatly affect and modify the surface topography; they frequently exercise an important control on surface and underground waters; they may become fissure veins by filling and replacement along their

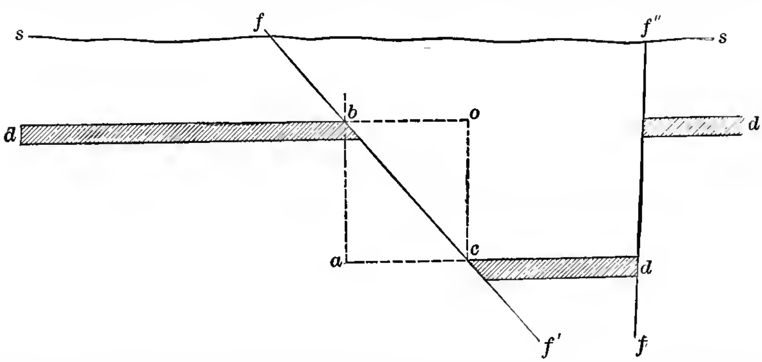


Fig. 107. — Normal fault in horizontal beds. *ss*, surface; *ff'*, fault plane; *db*, upthrow side; *dc*, downthrow side; *cba*, angle of hade or slope; *cbo*, angle of dip; *ab*, throw (also stratigraphic throw in this case); *ac*, heave (horizontal throw); left side of *ff'*, foot wall; right side of *ff'*, hanging wall; *fbc*, fault scarp; *f''f'''*, fault plane (vertical).

courses, and hence are of great economic importance in the formation of ore deposits (see Chapter XII); and they may prove to be causes of great disaster in loss of time and money in mining operations, unless properly interpreted and understood.

Fault terms.[1] — For clearness of discussion it is desirable to have

[1] The terminology of faults has been discussed in detail by a committee appointed by the Geological Society of America. Their conclusions are given in full in Bull. Geol. Soc. Amer., vol. 24, pp. 163–186, 1913.

terms to indicate the several features of faults. These are as follows: A *closed fault* is one in which the two walls of a fault are in contact. An *open fault* is one in which the two walls of a fault are separated. The same fault may be closed in one part and open in another. The *fault space* is the space between the walls of an open fault. A *fault surface* is the surface of a fracture along which dislocation takes place, and if without notable curvature it is called a *fault plane* (Fig. 107).

Fig. 108. — Fault in Ordovician slates near mouth of Slate River, Va. The two hammers mark boundary of fault breccia. (T. L. Watson, photo.)

A *fault line* is the intersection of a fault surface with the earth's surface, or with any artificial surface of reference, such as the floor of a tunnel. When a fault is made up of slips on closely spaced surfaces, with more or less deformation of the intervening rock, it is called a *shear zone*. The name would also be applicable to *breccia zones* (Fig. 109) which characterize some faults, especially those of the thrust type.

The *fault breccia* (Fig. 109) is the breccia frequently found in the shear zone, and more especially in the case of thrust faults. *Gouge* is the finely pulverized clay-like rock, which is often found between the walls of a fault. Both the fault breccia and gouge are the result of the crushing of the wall rocks during slipping. In the actual movement the blocks may scratch and polish the surfaces of one another.

These striated and polished surfaces are known as *slickensides*. A *horse* (Fig. 110) is a mass of rock broken from one wall and caught between the walls of the fault. The *fault strike* is the direction of the intersection of the fault surface, or the shear zone, with a horizontal plane. The *fault dip* (Fig. 107) is the inclination of the fault surface, or shear zone, measured downward from a horizontal plane. It is never greater than 90 degrees. The *hade* (Fig. 107) is the inclination of the fault surface, or shear zone, measured from the vertical; it is the complement of the dip. A fault hades to the side towards which it dips. The *hanging wall* (Fig. 107) is the upper wall of the fault, and the *foot wall* (Fig. 107) is the lower one.

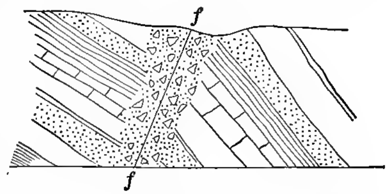


Fig. 109. — Faulting accompanied by brecciation.

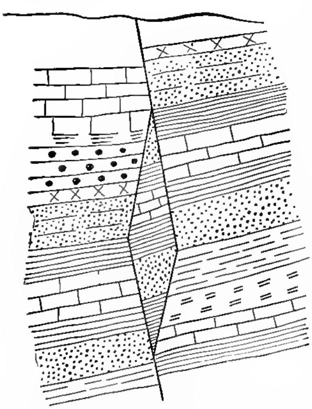


Fig. 110. — Section showing "*horse*" developed by faulting.

Criteria for faulting. — Various criteria can be used, but one alone seldom proves conclusive, and some may be developed under conditions other than faulting. Of the more important criteria which may be applied are: (1) Displacement of dikes (Fig. 106), veins or beds; (2) brecciation along line of fracture as a breccia zone (Fig. 109 and Fig. 108); (3) striations and polish on fracture surfaces (slickensides); (4) the presence of gouge; (5) the presence frequently of a shear zone or division of the rock into slices parallel to the plane of the fault; (6) the repetition or omission of beds; (7) fault scarps (Fig. 107), seen where faults are recent, and erosion has not had time to reduce them; (8) drainage lines sometimes developed along fault lines.

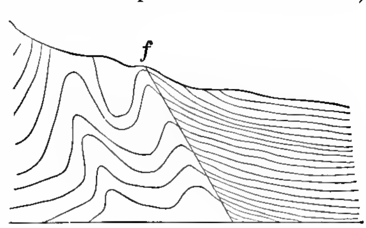


Fig. 111. — Normal faulting showing distortion of shale.

It must not be assumed that in the field the two walls of a fault will be found in contact at the surface, for the fault line or zone may be covered by surface material. The presence of the fault must then be determined from the structural relations of the surrounding outcrops on

opposite sides of the fault line or zone. All faults, however, do not extend to the surface.

Kinds of Fault Displacement

Slip. — The word *slip* indicates the displacement as measured on the fault surface, while qualifying words may relate to the strike and dip of the fault. The *slip* or *net slip* is "the relative displacement of formerly adjacent points on opposite sides of the fault, measured in the fault surface (Fig. 115)."

Shift. — Faults sometimes show not a single surface of shear, but a series of small slips on closely spaced surfaces. In some faults the beds near the fault surface are bent, so that the relative displacement of the rock masses on opposite sides of the fault may be different from the slip, and not even parallel with it. The word *shift* denotes the relative displacement of the rock masses situated outside the zone of dislocation while qualifying words relate to the strike and dip of the fault with one exception, in which the meaning is clear. The *shift* or *net shift* denotes the maximum relative displacement of points on the opposite sides of the fault and far enough from it to be outside the dislocated zone (Fig. 115).

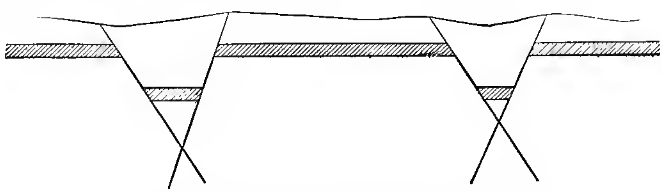


FIG. 112. — Diagram illustrating trough faults.

Throw and heave. — *Throw* (Fig. 107) is the vertical displacement between corresponding lines in the two fracture surfaces of a disrupted stratum, etc., measured in a vertical plane at right angles to the fault strike. The *heave* (Fig. 107) is the horizontal distance between corresponding lines in the two fracture surfaces of a disrupted stratum, etc., measured at right angles to the fault strike. A vertical fault has no heave, and a horizontal fault has no throw.

Throw and heave are essential elements of a fault. Thus, if a fault were encountered in the working of a coal bed, it would be important to know how far a drift should be run horizontally, and to what depth a shaft should be sunk vertically to reach the other part of the disrupted bed.

Faults in stratified rocks. — The character of the displacement of the beds in stratified rocks is so much influenced by the relation of

the strike of the fault to that of the beds that special classes may be recognized. A *strike fault* (Fig. 121) is one whose strike is parallel to the strike of the beds. A *dip fault* is one whose strike is approximately at right angles to the strike of the beds or parallel to the dip. An *oblique fault* is one whose strike is oblique to the strike of the beds.

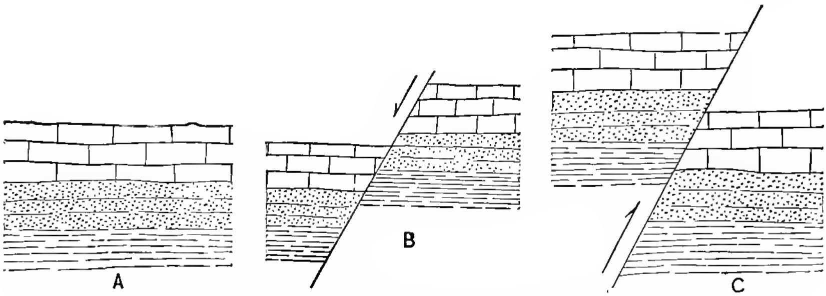


FIG. 113. — Sections showing development of fault, of either normal or reverse character. *A*, unfractured beds; *B*, normal fault; *C*, reverse fault.

These terms are not directly applicable in regions of unstratified rocks, but they might be used in such areas with respect to the strike of a system of parallel dikes if distinctly stated in the description of the faults.

Fault blocks. — Terms applicable to fault blocks are *fault wedge, horst,* and *graben* or *trough fault.* A *fault wedge* is a wedge-shaped

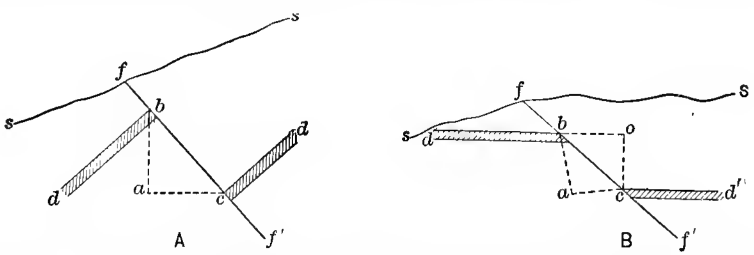


FIG. 114. — *A*, Normal fault hading against dip of beds. *B*, Normal fault hading with dip of beds. *ab*, throw (vertical); *bc*, stratigraphic throw; others same as Fig. 107.

block between two faults (Fig. 112). A *horst* is an upthrown block between two downthrown blocks; while a *graben* or *trough fault* is a downthrown block between two upthrown blocks.

Offset. — This is the distance between the two parts of a disrupted bed measured at right angles to the strike of the bed, and on a horizontal plane. Heave has been used by some for offset (Fig. 120).

General Classes of Faults

Faults classified according to nature of displacement. — A *normal fault* is one in which the hanging wall has apparently been depressed relatively to the footwall (Figs. 107, 113, 114, and 115). A *reverse fault* is one in which the hanging wall has apparently been raised relatively to the footwall (Fig. 113).

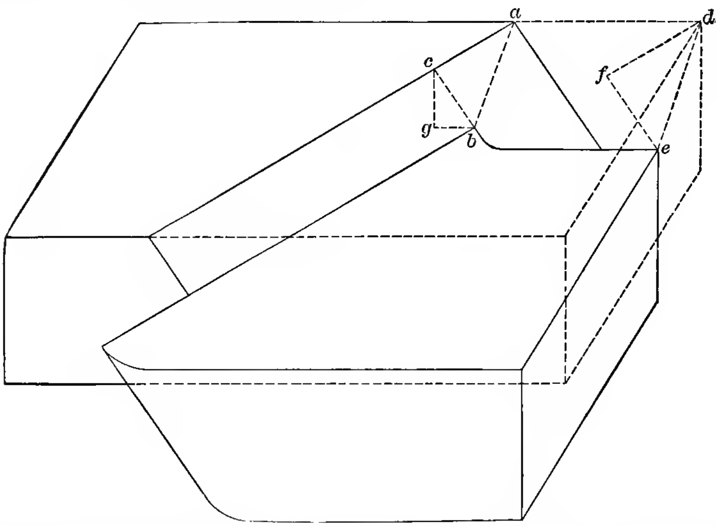


FIG. 115. — Faulted block with parts named. *ab* = slip or net slip; *cb* = dip slip; *ac* = strike slip; *de* = net shift; *fe* = dip shift; *gb* = heave; *gc* = throw. The fault movement is oblique. (After Reid.)

The relative displacement has usually been determined by means of a dislocated bed. The horizontal distance between two points on opposite sides of a fault, measured on a line at right angles to the fault strike, is shortened by a reverse strike fault, lengthened by a normal strike fault, and unchanged in length by a vertical fault.

The term *thrust*, used for ordinary reverse faults of low dip, may be applied to reverse faults known to be due to compression. *Overthrusts* are reverse faults with low dip or large hade. In some cases the dip-slip has been enormous, amounting to several miles. Faults of this type have noteworthy development in the southern Appalachians.

Effect of Faults on the Outcrop

The effect of faults on the outcrop (surface) may be of two kinds: (1) Topographic, and (2) geologic.

Topographic effects. — The expression of faults at the surface may be shown in escarpments, distribution of rocks of unequal resistance, drainage lines, etc. Faults frequently exhibit no surface expression, so that their existence might not be suspected. This is apt to be the

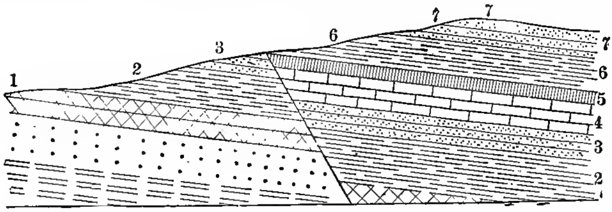


Fig. 116. — Strike fault section, hading with dip; cuts out some beds at surface.

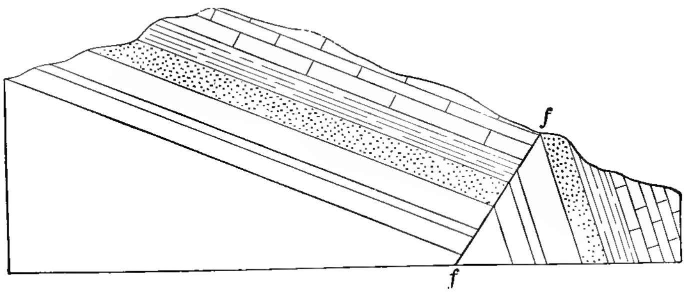


Fig. 117. — Fault showing change of dip.

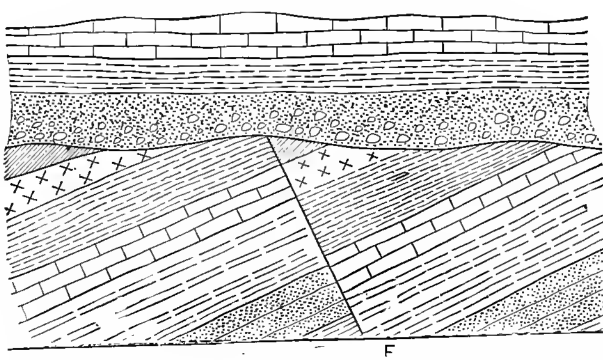


Fig. 118. — Faulting of an unconformable series of beds showing age of fault.

case in faults which have but slight displacement, or in those having originally moderate or great displacement resulting in the formation of a well-defined fault scarp, erosive processes having reduced the scarp (upthrow) side to an approximate common level with the opposite side. In many cases, however, a scarp that is of gentle or steep

slope and of moderate or considerable height, dependent upon the hade and amount of displacement, results from faulting. The Hurricane fault and the faults of the Basin Ranges are among the best examples of faults showing fault scarps. A sequence of surface forms

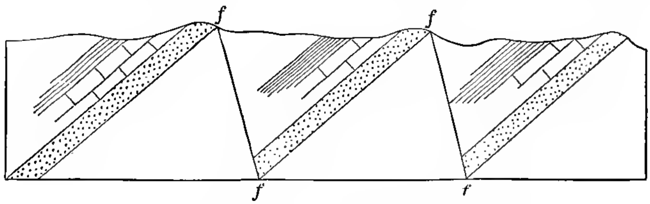


FIG. 119. — Strata repeated by faulting.

may develop during the progress of dissection and erosion, passing through youthful, mature, and old stages, until the fault scarp is finally obliterated upon completion of the cycle of erosion.

Again faults may bring together rocks of markedly different or unequal resistance, so that the more resistant rocks will rise above the

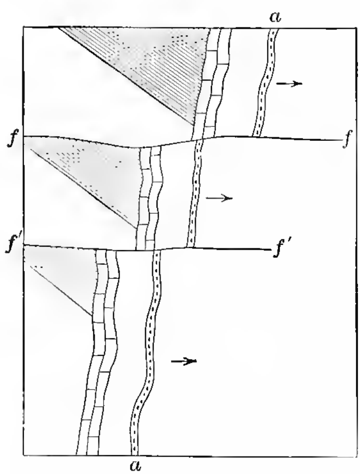


FIG. 120. — Plan illustrating shifting of beds by faulting.

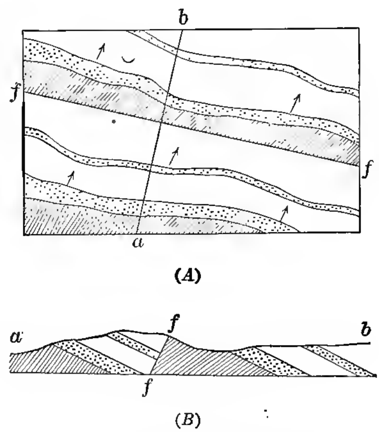


FIG. 121. — (A) Plan of strike fault showing repetition of beds at surface. ff, fault. (B) Section along line ab normal to strike fault showing repetition of beds.

softer ones, forming a more elevated belt, the margin of which is marked by the line of dislocation. The juxtaposition of a hard and soft rock however is not always proof of faulting, for we might have a soft limestone interbedded normally between two hard sandstones.

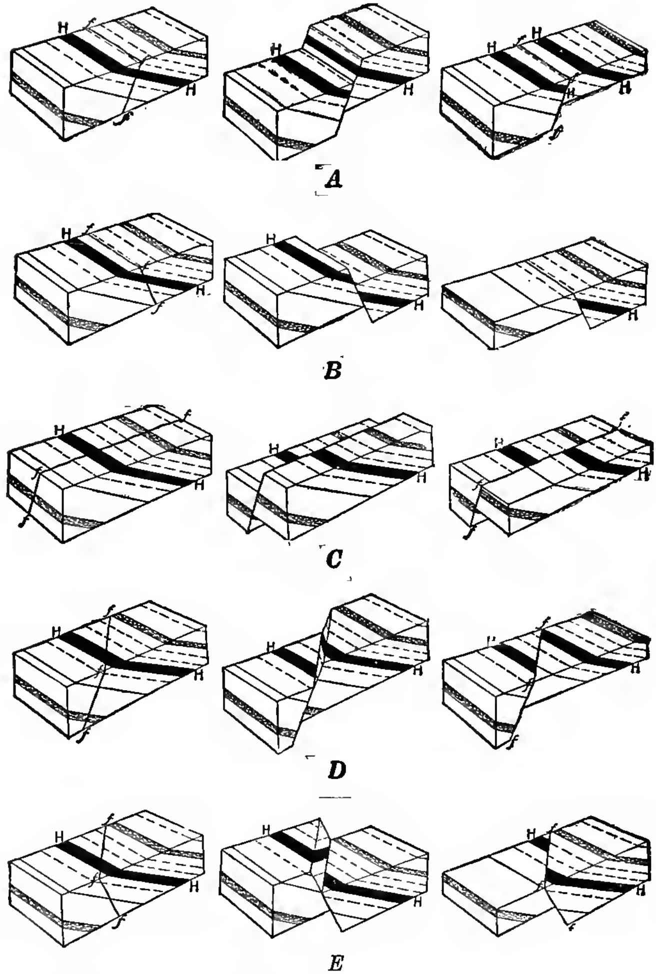


Fig. 122. — Diagram showing effects of different kinds of faults on block with monoclinal structure and one coal bed. Fault fissure, *f*. The block is supposed to have been worn off in each case after faulting. *A*. — Repetition of beds by normal strike fault hading in opposite direction from dip. *B*. — Cutting out of bed by strike fault hading in same direction as dip. *C*. — Horizontal separation of bed, by dip fault whose downthrow side is on farther side of fault plane. *D*. — Overlapping of bed by oblique fault. *E*. — Separation of bed by oblique fault. (Chamberlin and Salisbury.)

If the series of beds had a steep dip, a depression might be worn on the easily eroded limestone, while the resistant sandstones remained as bordering ridges on either side.

The courses of faults are sometimes marked by lines of springs; they may also become lines of control for surface drainage, the erosion along them developing valleys.

Geologic effects. — Faults may produce various complications in the outcrops of rocks at the surface.

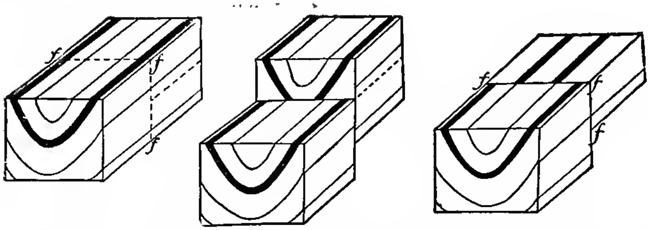


FIG. 123. — Diagram showing effect of faulting on the outcrops of a syncline. (From Chamberlin and Salisbury, College Geology.)

Strike faults may repeat a given layer or bed at the surface (Fig. 121) or may eliminate or cut it out altogether (Fig. 122*B*), dependent upon whether the downthrow is against or in the direction of the dip of the beds. Dip faults cause horizontal shift of the outcrops, either forward or backward, according to the direction of downthrow (Fig. 122*C*). Oblique faults result in offset with overlap if the downthrow is to the left (Fig. 122*D*), or offset with gap, if the downthrow is to the right (Fig. 122*E*). The amount of overlap and gap increases with increase of throw and hade, and decreases with increase of dip.

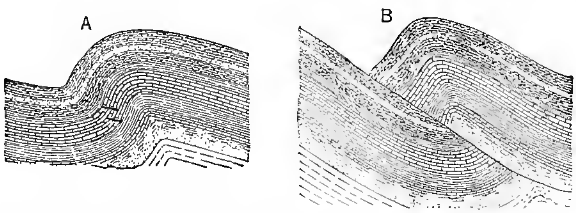


FIG. 124. — (*a*) Stepfold, showing break in the massive limestone bed which determines the plane of the break-thrust, (*b*) along which the displacement results from further compression. (Willis.)

A fault which crosses a fold at right angles to its axis changes the distance between the outcrop of a given bed on opposite sides of the fault; the distance being decreased on the upthrow side of a syncline (Fig. 123), and increased on the upthrow side of an anticline.

Various other complications arise under different conditions, but these will serve to indicate the effect on outcrop which may result from some of the common kinds of faulting.

Relation between faults and folds. — From earth movements which result in over-intense folding, folds may pass into faults both vertically and horizontally. Beds involved in such cases often show thickening and thinning, stretching and shortening. Frequently in monoclinal folds, these may pass into a fault when followed along the strike. This may be because the fold is so strongly compressed or drawn out that the flexure disappears and a fault takes its place. Thus in the Kaibab fault of the high plateaus of Utah, a normal fault grades along the strike into a monocline.

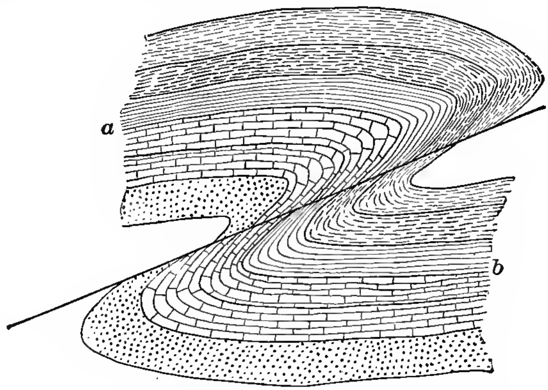


FIG. 125. — Fold passing into a fault. (Van Hise.)

In the southern Appalachians overthrust faults are frequently found associated with overthrust folds. There may also be found in the same region excellent examples of distributive faults associated with minute overthrust folds.

Relation of Faulting to Engineering Work

Faulting is a common phenomenon in many regions of disturbed rocks. It causes engineers trouble not only for the reason that it has in the past disturbed the rock formations, but sometimes because fault movements take place at the present time. Several cases may be noted.

Tunneling. — The importance of having firm solid rock to tunnel through is well recognized, not only as a matter of safety and convenience in working, but for easy maintenance after the tunnel is completed. If, therefore, a rock which has been pierced by a tunnel is much shattered by faulting, it becomes necessary to line the tunnel, at least in the crushed territory. Furthermore, if the fault fissure extends to the surface, it may serve as a channel way for rain waters (Fig. 126).

A most interesting case was developed on the line of the Canadian Pacific Railway between the summit of the pass at Hector, B. C., and Field, B. C., in the valley of the Kicking Horse River. In order to reduce the grade between these points, the road was lengthened and two spiral tunnels were constructed. The upper tunnel was in the

quartzite of Cathedral Mountain on the south side of the valley (Fig. 127), while the lower one was in the limestone of Mt. Ogden on the north side. Now it happens that a fault of nearly 3000 feet displacement passes between Cathedral Mountain and Mt. Stephen to the west of it, and the upper tunnel lies partly within the shear zone of the fault. This has given much trouble, first, because of the shattered character of the rock, which necessitated lining the tunnel, and, second, because of the surface water which ran down along the fissured zone. The lower tunnel in the massive limestone of Mt. Ogden is free from these annoyances.[1]

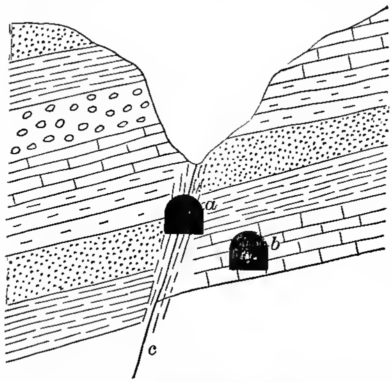


FIG. 126. — Section showing relation of tunnel to fault zone.

Another interesting case [2] is that of a tunnel at Franklin, California, which follows the soft clay gouge of a thrust fault. The tunnel is timbered, but the swelling of the wet clay dislodges the wooden supports. A geological examination of the ground at the time of the railroad survey might have avoided the trouble.

Aqueducts. — In aqueduct construction engineers have had to deal not only with past but with present faulting. In the selection of a route for the new Catskill aqueduct, in New York state,[3] much of the construction was tunnel work, especially where it became necessary to cross under river valleys with inverted syphons. Consequently, in the selection of a route which would insure solid rock for as great a distance as possible, much attention was given to the occurrence of faults, which might have shear zones of variable width. Such lines of fracture were encountered at several places.

At times the existence of faults can be inferred or even definitely determined from drill records. If, for example, in boring, the beds encountered are in an order known not to be the normal one for the rocks of that region, and the drill also strikes crushed or brecciated zones, faulting may be inferred. Occasionally the drill on meeting fault fissures is deflected.[4]

The movement which produced the San Francisco earthquake in

[1] Oral communication from Prof. J. A. Allan.
[2] Oral communication from Prof. A. C. Lawson.
[3] Berkey, N. Y. State Museum, Bull. 146, 1911.
[4] Berkey, N. Y. State Museum, Bull. 146, p. 166, 1911.

1906 took place along a fault fissure traceable for at least 250 miles, and although having a small horizontal displacement (8 to 20 feet) it did considerable damage. Pipe lines which crossed the fracture, and in one case a water supply tunnel connecting two lakes, were broken.

FIG. 127. — View from Mount Stephen, near Field, B. C., looking towards pass at Hector. On right slope are seen the two ends of the upper tunnel crossing fault zone in mountain on right. On extreme left, slope of Mt. Ogden, where the lower spiral tunnel is in massive limestone.

The recently completed Los Angeles aqueduct, which brings water from Owens Lake to Los Angeles, California, must of necessity cross fault lines; hence, there is always the possibility of damage if further slipping occurs along any of these fractures.

Earthquakes. — Fault movements are a frequent cause of earthquakes, and the vibrations set up in the rocks by faulting cause more or less damage, sometimes for a distance of several miles from the fault line. Structures standing on hard rock are less violently shaken (other things being equal) than those on unconsolidated material.

The problem which confronts the engineer in countries subject to

such shocks is to determine what type of structure will best resist the disturbance.[1]

Coal mines. — In some coal fields like those of the southern Appalachians, the beds are not only folded but are sometimes faulted. The effect of this is: First, that the two parts of a fractured bed may become completely separated so that the engineer, especially if he lacks geological knowledge, may have difficulty in discovering the continuation of the bed on the other side of the fracture; and second, the coal along the fault is usually badly crushed, and even mixed with rock and dirt.

Ore deposits. — Mining engineers probably have more trouble with faults than any other class of engineers.

Mineral veins are frequently formed by the filling of fault fissures (see Chapter XII). If, now, there is more than one set of fissures of different age in a given region, and those of one series are mineralized, while those of the other series are of much less importance (as at Butte, Mont.), it is highly essential for the engineer to recognize this fact, in order to avoid following barren leads.

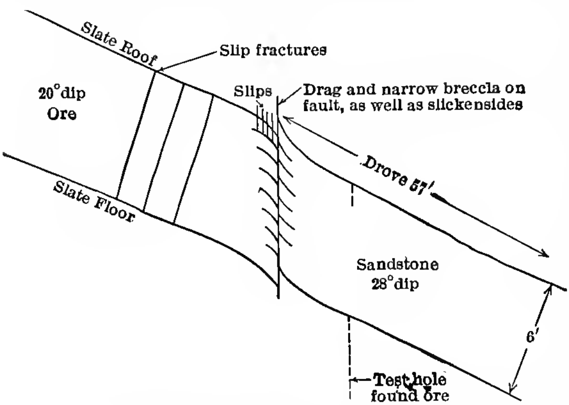


Fig. 128. — Section showing case of bedded ore cut off by fault.

But aside from this, ore veins and other types of ore bodies are sometimes displaced by one or more later faults. The engineer or mining geologist must then determine, if possible, the amount and direction of the fault movement in order to find the continuation of the ore body.

Abundant and complex faulting sometimes makes the problem an exceedingly difficult one.[2]

[1] See Gilbert and others, U. S. Geol. Survey, Bull. 324, 1907, San Francisco Earthquake and Fire, and Effects on Structures and Structural Materials; Hobbs, Construction in Earthquake Countries, Eng. Mag., XXXVII. p. 1, 1909; Milne, Construction in Earthquake Countries, Trans. Seismol. Soc., Japan, XIV, p. 1, 1889–1890; Hobbs' Study of Damage to Bridges during Earthquakes, Jour. Geol., XVI, p. 636, 1908; Hobbs, Earthquakes, Appleton, New York, 1907. The Bulletin of the Seismological Society America contains many valuable papers.

[2] See Lindgren, Mineral Deposits, p. 115, 1919; Spurr, U. S. Geol. Survey, Prof. Pap. 42, 1905, on Tonopah, Nev.

Curiously enough engineers sometimes on coming to a fault plane think that the ore has given out, although the evidence of displacement such as slickensides and breccia, may be present. A simple, and almost self-explanatory, case found in a bedded ore deposit in the eastern states is given in Fig. 128. Many others more or less complex can be found in the literature.

Oil and gas. — The crossing of an oil or gas pool by a fault may allow these substances to escape to the surface. In the case of the former, however, the oil sometimes changes to asphalt which seals the fissure.

Submarine cables. — Faulting appears to have been responsible occasionally for the breaking of a submarine cable. This caused the breaking of the lines near Valdez, Alaska, during the earthquake shock of Feb. 14, 1908.[1] Similar trouble was caused in Porto Rico and Jamaica.[2] It should be explained that the breaking of the cable was due to submarine slides started by the earthquake.

It is stated that both the Valdez-Sitka and Valdez-Seward cables were interrupted close to the city of Valdez, and well inside Valdez Narrows. The Valdez-Seward cable was broken in four places three-eighths to one and one-eighth miles apart, while the Valdez-Sitka cable was broken in seven places five-eighths to seven-eighths mile apart.

Landslides. — As explained in Chapter VII fault fissures which contain clay gouge and become wet and slippery by infiltrating waters may serve as gliding surfaces which cause landslides. Slips of this type were among those encountered in the construction of the Panama Canal.

Rock Cleavage

Definition. — The term *rock cleavage* as used in its broadest sense, and only in a structural one, includes the property which many rocks possess of splitting along parallel surfaces in certain directions more readily than in others.

Kinds of cleavage. — Two types of rock cleavage may be recognized, viz., *original* and *secondary*. The former would include such structures as bedding and lamination in sedimentary rocks, flow structure in lavas, etc.; in other words, all original planes of low cohesion along which the rock may split. The latter would include parallel structures which have been induced in rocks by metamor-

[1] Tarr and Martin, U. S. Geol. Survey, Prof. Pap. 69, p. 97, 1912.

[2] Reid and Taber, The Porto Rico Earthquake in 1918, Document 269, House of Representatives.

phism subsequent to their formation, and includes such structures as true cleavage, slatiness, schistosity, foliation, fissility, etc. By most geologists the term *rock cleavage* is applied to secondary structures only. Secondary cleavage is subdivided into (1) *fracture cleavage* and (2) *flow cleavage.*

Fracture cleavage. — Fracture cleavage [1] is the structure developed when a rock under stress breaks along closely-spaced, incipient, parallel joints. The term *fissility* is applied to such partings.

In many quarries the rock appears massive, but when struck with a hammer, the stone breaks along definite planes. Such structural weaknesses are known to the quarryman as *blind joints.* They are common in the older crystalline rocks, constitute lines of weakness, and prevent the use of the rock for dimension blocks.

Fracture cleavage is independent of any parallel arrangement of the minerals, and there may be two or more intersecting sets of planes. It is developed in the zone of fracture.

Flow cleavage. — In flow cleavage (cleavage proper) the capacity of the rocks to part along parallel surfaces, not necessarily planes, is dependent on a parallel arrangement of the mineral constituents. It is developed in the zone of flowage and includes the cleavage of most writers. *Slatiness* or *slaty cleavage* of slates, *schistosity* or *foliation* of schists, and *banding* or *gneissic structure* of gneisses are all phases of it. (See slate, schist, and gneiss.)

Origin of Folds, Faults, Joints, and Cleavage

Introduction. — When subjected to stresses of sufficient intensity rocks are deformed either by fracturing or by flowing. Among the chief factors involved in the deformation are the character of the rocks, the presence of moisture, and the depth of burial. Based upon the character of the deformation of rocks, when subjected to differential stresses, the outer crust of the earth may be divided into an upper *zone of fracture* and a lower *zone of flowage.*

In the zone of fracture the rocks are deformed mainly by fracture. The structures produced in this zone are joints, faults, fracture cleavage, and brecciation. The maximum depth of the zone of fracture is 11 miles or 17,600 meters.[2]

Below this depth is the *zone of flowage,* within which all rocks deform by flow. Deformation is produced by granulation, recrystallization, and rotation. No openings larger than those of microscopic size are produced, since larger ones would be closed by pressure. Rock flowage results in a parallel arrangement of the rock constituents producing foliation. The structures produced are flow cleavage, schistosity, and gneissic banding.

Folds may be developed by either fracture or flowage, and frequently by both combined.

[1] Other names for fracture cleavage are close-joint cleavage, false cleavage, strain-slip cleavage, slip cleavage.

[2] Jour. Geol., XX, p. 97, 1912.

Some rocks like shales may deform by flow at a comparatively slight depth below the surface, while for the same depth other rocks like sandstone would deform by fracture. Because of this varying susceptibility of different rocks to deforming influences much of the zone of fracture is a *zone of combined fracture and flowage.*

It can be shown experimentally that if rocks in a confined position are subjected to sufficient pressure, the amount depending on the kind of rock, they can be deformed without fracturing.

With this explanation we may consider a little further the origin of some of the structures discussed in the preceding pages.

Cause of folds. — Folds are the result of compressive forces incident to shrinkage of the earth's crust, due probably to contraction of the earth.

FIG. 129. — Beds of slate, showing cleavage, overlain by quartzite. The bedding of the slate which does not show in the view is parallel with that of the quartzite. Field, B. C. (H. Ries, photo.)

When folding develops in the zone of fracture it is probably caused by the rocks slipping along planes of jointing, faulting, or cleavage. But when developed in the zone of flowage the rocks become practically plastic and the folding may be due either to the mineral particles gliding one upon the other, or actually changing their individual shapes, or in part dissolving in points of higher pressure and recrystallizing at points of less pressure. Factors affecting the result are the degree of rigidity of the beds, rate of application and duration of pressure, and depth below the surface.

All folds result from yielding to pressure, and field studies show that rocks have varying degrees of competence, so that in areas of folding the weaker beds have been controlled by the stronger or more competent beds. In a series of interbedded quartzites and shales the folding of the rigid, competent beds of quartzite might very well show the characteristics of the zone of fracture, while the associated weaker and *incompetent* beds of shale would, from development of cleavage, characterize the zone of flow (Fig. 129). In such a series the rigid, *competent* beds of quartzite sometimes exhibit little or no folding, while the weaker, incompetent beds of shale are folded, the quartzite being in the zone of fracture and the shale in the zone of flow, as indicated by the development of cleavage in the latter. This principle is well exemplified in parts of the Valley region of Virginia, in which beds of limestone have been deformed (folded) by fracturing, while the associated beds of shale have been deformed by flow.

Cause of joints. — Joints are limited to the zone of fracture, and may occur in rocks of both disturbed and undisturbed regions. While their horizontal distribution may be great, they are limited vertically by the depth of the zone of fracture. Joints have been referred to many causes, but a discussion of them is not contemplated here. They have been formed both by tension and compression, hence we recognize in their classification *tension joints* and *compression joints.* For certain lines of structural geologic work their discrimination is of importance.

Cause of cleavage. — Fracture and flow cleavage are due to compressive forces, but fracture cleavage, including fissility, is probably more characteristic of the harder rocks, and slaty cleavage of the softer ones. Composition and fineness of division of the mineral particles also affect the result.

Fracture cleavage is developed in the zone of fracture, and is independent of the parallel arrangement of the minerals, but such parallel arrangement as is sometimes seen in chlorite and mica may result from rubbing on fracture planes. If at the same time the cleavage planes are closely spaced it may be difficult to distinguish from flow cleavage. Normally, fracture cleavage planes are more widely spaced than flow cleavage planes, and moreover they may be developed in two or more intersecting sets.

Flow cleavage means parallel dimensional arrangement of the mineral particles. It results from differential pressure in the zone of flow, causing the rock to deform by flowage and not by fracture; it therefore involves a combination of physical and chemical changes. The processes which bring about the parallel arrangement of the mineral particles are: (1) *Crystallization* and *recrystallization* resulting in the flattening of old minerals and development of new ones in the planes of easiest relief, and (2) *rotation and granulation of the original minerals,* such as quartz and feldspar. Gliding along definite planes of some minerals, especially calcite, will also result in flattening of the mineral particles, and consequently in parallel arrangement.

Structures Due to Erosion

Under this head are discussed several structures, (1) unconformity and overlap, and (2) inliers and outliers, which owe their origin in most

cases to erosion, although they may be the result at times of faulting and folding.

Unconformity. — Strata that have been deposited one above another in orderly sequence, so as to form a continuous succession of beds, are said to be *conformable* and the structure is known as *conformity* (Fig. 90). In a conformable series the beds are usually parallel to one another.

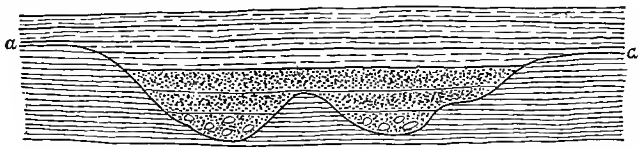


FIG. 130. — Section showing disconformity *aa*, strata horizontal.

In many places, however, this orderly succession of beds has been interrupted by cessation in deposition for a period of time, represented by a break in the geological record, and marked by an erosion interval of more or less magnitude. There has been a loss of a part of the geological record. The formations are discordant and are said to be *unconformable,* the structure being called *unconformity* (Figs. 130 and 131).

Two main groups of unconformities are generally recognized: (1) *Disconformity* when the two formations are in parallel position, the erosion line between which may or may not be entirely visible (Fig. 130); and (2) *non-conformity* or *angular unconformity* when the line of unconformity is plainly visible between the beds of the lower series, when tilted if composed of sedimentary rocks or of unstratified rocks, and the beds of the series above (Fig. 131).

Unconformities are of great importance in the interpretation of geological history. Thus in Fig. 131 the structure indicates that the conformable series of lower inclined beds was first deposited under water in horizontal position, or nearly so, and afterwards raised, tilted, or folded into a land surface. After elevation to a land surface, the beds were subjected to a long period of erosion whereby they were reduced to a nearly common level. They were then depressed beneath the water, and the upper or second set of beds was deposited on them, the whole being finally elevated to form a land surface. The two sets of beds are discordant as shown in (1) dissimilarity of dip, (2) an erosion interval and therefore a hiatus or time break, and (3) in a coarse conglomerate bed forming the basal member of the upper conformable series of horizontal beds.

Discordance of dip is not to be interpreted in every case as indicating unconformity, for it results from various causes, such as faulting, folding, etc. Moreover, unconformities occur in horizontal beds in which the two series of beds exhibit similarity of dip, as shown in Fig. 130. (See above under *disconformity.*)

Unconformities are not limited to groups of stratified rocks, but are sometimes observed between stratified and igneous rocks (Fig. 132), and between stratified and metamorphic rocks.[1] The line of contact between two unconformable series of beds is sometimes a line of weakness and decay that may cause trouble in underground work.

[1] For a detailed discussion of the criteria of unconformity see Van Hise, U. S. Geol. Survey, 16th Ann. Rept., p. 1, 1896.

Overlap. — Overlap defines the relation between members of a conformable series of rocks, and is dependent on the existence of an unconformity. In a conformable series overlap is shown when an upper bed extends beyond the limits of

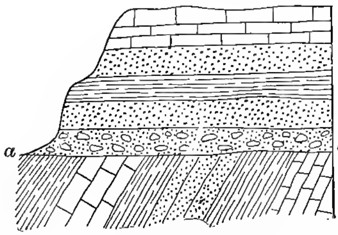


Fig. 131. — Section showing angular (non-conformity) unconformity *aa*.

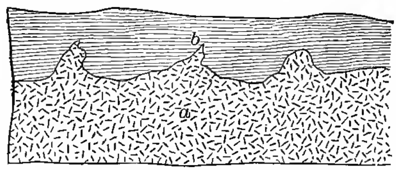


Fig. 132. — Igneous unconformity between (*a*) granite, and (*b*) sedimentary rocks.

the one or ones below, so that the edges of the lower bed or beds are concealed. If marine, the structure indicates either advance of the sea (*transgressive overlap*) on the land, or recession of the sea from the land (*regressive overlap*). Marine trans-

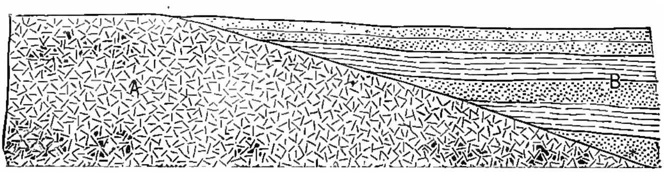


Fig. 133. — Section along contact of Piedmont crystalline rocks (*A*), and Coastal Plain sediments (*B*), showing overlap.

gressive overlap is well illustrated in the eastern United States in the overlapping beds of the Coastal Plain onto the older crystalline rocks of the Piedmont Plateau (Fig. 133).

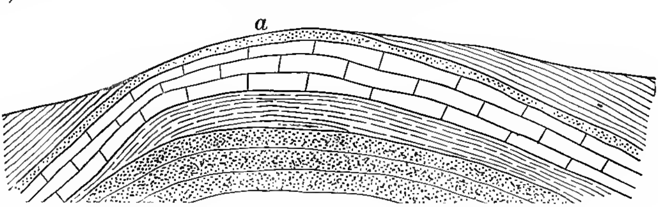


Fig. 134. — Section showing an inlier (*a*) formed at summit of an anticline by erosion.

Overlap is of much practical importance in mining operations as well as in questions of water supply, and failure to recognize this structure has led in some places to disappointment and loss. Well-known cases of this kind, especially those relating to the exploitation of coal beds, are reported both from this country and abroad.

Inliers. — An inlier represents outcrops of rocks surrounded on all sides by geologically younger rocks. It is usually the result of erosion, and is often observed in valleys or similar depressions. Thus in some of the southern states, isolated outcrops of granite belonging to the Piedmont crystalline rocks are observed some distance east of the fall-line, chiefly along or near stream courses but lying well within the limits of the Coastal Plain, and surrounded by the younger rocks of this province.

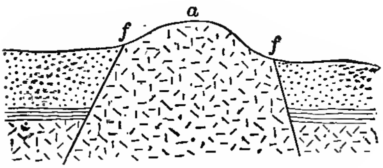


FIG. 135. — Section showing an inlier (*a*) formed by faulting. *ff*, faults.

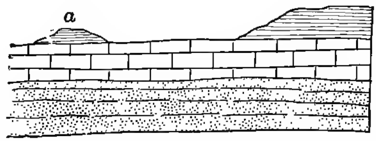
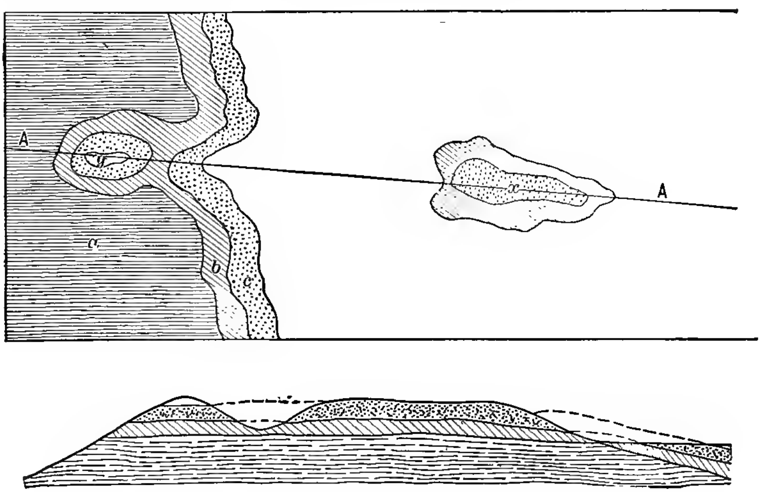


FIG. 136. — Section of outlier (*a*) formed by erosion.

Sometimes an inlier is observed on the crest of an eroded anticline (Fig. 134), and again as the result of faulting, as shown in Fig. 135.

Outliers. — An outlier represents an isolated portion of rock separated from the main mass and surrounded by geologically older rocks (Figs. 136 and 137). Outliers



Section along A A

FIG. 137. — Plan and section of outlier (*y*) and inlier (*x*). Section along line *AA*.

are usually the result of denudation and are of frequent occurrence in areas of strong erosion. They frequently occur capping hills and ridges, and may owe their existence to either the resistant character of the rock composing them or their geological structure, or both. They may be separated from the parent mass by a long or short distance.

Outliers may sometimes be the direct result of faulting, as shown in Fig. 138. According to their mode of formation we may recognize, (1) *erosion outliers,* the most common; and (2) *faulted outliers.*

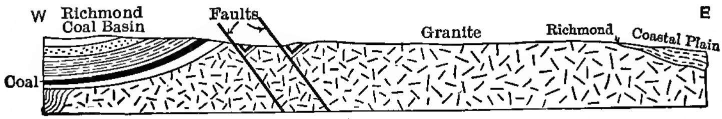


FIG. 138. — Outliers formed by faulting.

CONCRETIONS

Form and occurrence. — Concretions or nodules are bodies of foreign material, of usually more or less rounded shape, found mostly in sedimentary rocks, and of later origin than the material containing them. They are often nearly perfect spheres, or again flattened with elliptical outline, and in still other cases assume grotesque forms, causing some to mistake them for fossilized animal remains. They are often formed about a nucleus which may be a fossil, or some inorganic substance, such as a grain of sand. They vary from a fraction of an inch in diameter to several feet. Some contain a central cavity, and one form, which is divided by radial cracks filled with mineral matter, is known as a *septarium.* Concretions are usually harder and more resistant than the inclosing rock; hence they often stand out in more or less strong relief on the weathered surface (Fig. 65).

While it is known that concretions are of later age than the inclosing rock, still their exact mode of formation is not always clearly understood. Many of them represent a segregation of foreign matter around some nucleus about which they have been built up.

The materials forming concretions, and the kinds of rock in which they often occur are: (1) Flint or chert in limestone (Fig. 65) and chalk; (2) pyrite, in coal, shale, and slate; (3) iron carbonate in clays and shales; (4) clay and lime carbonate in clays (Fig. 139); (5) cemented sand grains in sands; (6) gypsum in clays and shales; and (7) barite in some sands and clays; etc. Some concretions are very pure, but they are often impure from the presence of the rock material.

Practical considerations. — Concretions are rarely of economic value, but on the contrary are usually a source of trouble.

Iron carbonate concretions, when found in clays or shales, are sometimes used as a source of iron ore, if sufficiently abundant, and not too high in impurities.

Flint nodules of some of the European chalk deposits, which have become rounded after being washed out of the cliffs and rolled by wave action, are used in ball mills. They are undesirable in limestones

used for structural work or in cement manufacture. They interfere with the dressing and polishing of the stone.

In clays or shales which are to be used for brick or sewer-pipe manufacture, concretions will, unless removed or crushed, be the cause of various troubles, such as cracking, pimples, fused spots, etc. Gypsum nodules found in shales are never a commercial source of that material.

Fig. 139. — Lime carbonate concretions at Hopyard, Rappahannock River, Va.

Pyrite nodules in coal lower its market value, because they raise its sulphur content, while in slate they injure its durability and appearance. In some coals the pyrite concretions, known as *coal brasses*, are present in such quantity as to be of commercial importance in the manufacture of sulphuric acid.

METAMORPHISM

Introduction. — Broadly speaking, metamorphism includes any change in the constitution of any kind of rock. Under a given set of conditions, minerals tend to form in rocks under those conditions, which remain permanent, that is, they tend to adapt themselves to their new environment. The adjustment, however, of a rock to new conditions takes place slowly, so that it may remain essentially under the same conditions for a long period of time.

The conditions under which rocks alter may be those of ordinary pressure and temperature at or near the surface, or they may be those of high temperature and pressure which exist at some depth below the surface. A rock mass may be subjected alternately to each of these conditions. Most changes in rocks take place under conditions that cannot be directly observed, but can only be inferred, such as all changes below a mile in depth.

Definition. — Metamorphism might be defined as any change in any rock, regardless of origin, and may be the result of chemical or physical agencies, or both. If such changes take place at or near the surface we call them *weathering*, but if they go on at some depth below the surface and involve greater hardness, densification, recrystallization, or change in mineral composition we call them *alteration* or metamorphism proper. The subject of *weathering* is treated in Chapter IV, so that the discussion here is restricted to the deep-seated changes in rocks.

Metamorphism may vary greatly in intensity. In some cases the rock has been so slightly changed that its original characters are still evident, but in others the metamorphism has been so complete as to obscure all trace of the original character of the rock, so that it becomes conjectural as to what its original nature was, whether igneous or sedimentary. Such metamorphism of a rock may result in partial or complete change of texture, structure, or mineral composition. Thus, a sandstone may be changed to a quartzite, in which only a change of texture has been involved, while that of structure and mineral composition remain unaffected. It frequently happens, however, that a rock, after metamorphism, especially under conditions of deep burial, shows no change in chemical composition, but a pronounced one as to mineral composition and structure. Thus, a pyroxene-bearing rock, such as dolerite, might be transformed into hornblende schist, which would be both a structural and a mineralogical change. Igneous rocks, such as granite, diorite, gabbro, etc., may be rendered gneissic without essential change in either chemical or mineral composition. A change of structure (foliation), however, in igneous rocks may not be the only one involved.

Agents of metamorphism. — The principal agents of metamorphism are (1) mechanical movements of the earth's crust and pressure; (2) liquids and gases; and (3) heat. All of these are considered necessary to the complete metamorphism of a rock, but not necessarily to the same degree, since one of them may be predominant in producing the change in one case, and some other in another.

Mechanical movements and pressure (dynamic metamorphism). — Downward pressure (sometimes referred to as *static* pressure) alone exerts little or no metamorphic effect because many sediments which have been deeply buried and subsequently uncovered by erosion show little evident change except consolidation.[1] Earth movements, on the other hand, are very effective in producing changes in rock masses, as

[1] Some geologists believe that static metamorphism is of considerable importance and that new minerals developed as a result of it are of equidimensional character.

shown in the production of folds and the accompanying structures, such as joints, faults, and of foliation in some or all of the involved rocks. Shearing stresses are set up as a result of pressure, which results in differential movement of the rock constituents, as shown in the broken fragments that are often flattened and elongated in the direction of shear. The degree of change will depend upon the intensity of compression and the depth at which it operates. Earth movements when accompanied by heat and water effect important chemical changes, and frequently result in the production of new minerals. That rocks are under strain is sometimes shown by the distortion of circular drill holes after they have been bored.

Liquids and gases. — Of these water is the most abundant and therefore the most important. Whatever its source may be, whether meteoric or magmatic, water is an effective agent of metamorphism. The rôle which water plays in producing rock changes is a chemical one, and it becomes most effective when accompanied by heat and pressure.

Water acts as a solvent of nearly all rock-forming minerals, slowly transferring mineral matter from one point to another, which aids crystallization. It is partly taken up into the molecules of new minerals, such as staurolite, epidote, mica, etc., and it is necessary to their formation. It is further aided by the substances which it may carry in solution, such as the emanations (fluorine, boric acid, etc.) given off from intrusive magmas, and which can only account for the formation of such minerals as tourmaline, vesuvianite, etc.

Heat. — The heat involved in metamorphism may come from several different sources: (1) Interior of the earth, which increases with depth, (2) developed from earth movements, and (3) from the intrusion of molten magmas. Whatever the source, heat is a most potent agent of metamorphism, as shown by the results of contact or local metamorphism discussed on page 150. Heat greatly increases the solvent action of solutions, and it promotes the formation of new minerals.

Zones of metamorphism. — As already explained, the changes in rocks near the surface are quite different from those at depth. Based then on depth which is regarded as an important geological factor in determining the character of the alteration, we recognize two zones, viz.: (1) An upper or *katamorphic* zone in which mineral compounds are broken down into simpler ones, and a lower or *anamorphic* zone in which simple compounds are built over into more complex ones. The upper part of the zone of katamorphism, which extends to the groundwater level (see Chapter IV), is the *belt of weathering,* and the lower part has been called the *belt of cementation.*

Katamorphic zone. — The limits of the zone of katamorphism are essentially those of the zone of fracture (p. 140). The alterations that take place in the belts

of weathering and cementation are strongly contrasted. The characteristic reactions of the belt of weathering (discussed in Chapter IV) result in solution, decrease of volume, and softening of the materials. On the other hand, the belt of cementation is characterized by deposition, increase of volume, and induration of the materials. The materials dissolved from the belt of weathering are carried downward into the belt of cementation and there deposited. It must not be misunderstood, however, that solution may and does go forward in the belt of cementation.

Anamorphic zone. — The zone of anamorphism corresponds to the zone of flowage, in which there is great pressure in all directions. It is a zone of *reconstruction*, and is especially characterized by silication involving decarbonation, dehydration, and deoxidation; the minerals formed are numerous, of high specific gravity, and probably of complex structure.

Kinds of metamorphism. — For convenience of discussion, we may divide metamorphism into (1) *Contact* or *local metamorphism*, and (2) *general* or *regional metamorphism.* These two kinds of metamorphism are generally recognized by most geologists, and especially the economic geologist, as having an important bearing on the formation of ore deposits.

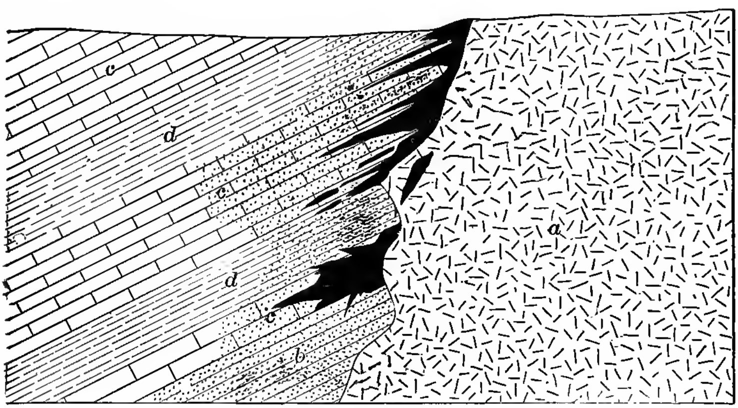


FIG. 140. — Section through a contact metamorphic zone; showing (*a*) intrusive rock; (*b*) quartzite; (*c*) limestone; (*d*) shale. Contact metamorphic zone shown in stippled area, including ore in black.

Contact metamorphism. — By contact metamorphism is meant the changes produced by intrusive magmas in contact with other rocks which they invade. The rock invaded may be either sedimentary, igneous, or metamorphic, but the most pronounced changes are shown in sedimentary rocks, especially limestones. This is because the siliceous crystalline character and dense texture of the igneous and metamorphic rocks make them more resistant to alteration.

The changes which result from contact metamorphism may affect

both the intrusive and the intruded rocks at or near their contact. Those developed in the intrusive body and referred to as *endomorphic changes* may include change both in mineral composition and in texture, the latter being the more common. The border changes in chemical composition may be due to magmatic differentiation (p. 43), or to the presence of mineralizers (p. 40), which tend to be squeezed out towards the margin as the interior solidifies, and collect there. The textural change may be shown by finer grain due to chilling of the outer portion of the intrusive mass, or in other cases a porphyritic texture is developed.

Changes which affect the intruded rocks are known as *exomorphic changes*. They depend on the character of invaded rock, the size of intrusive, the character of vapors expelled by the intrusive during solidification, and the structural features and position of beds of the country rock. The area in which the exomorphic changes occur is known as the *contact zone*, and is of variable width, being one or even two miles in some cases, but usually much smaller as well as irregular.

The changes are usually most pronounced in sedimentary rocks, such as limestones, clay shales and slates, and to a less extent in sandstones. Shales and slates are baked to a hard siliceous rock called "hornfels," while limestones are converted into marble, and sandstones are usually changed to quartzites. New minerals are developed, and these are especially abundant in limestone, where they are of both metallic and non-metallic character. Indeed the former are often in sufficient abundance to form ore-deposits [1] (Chapter XII). Igneous and metamorphic rocks are usually less altered by contact metamorphism, but there are many exceptions to this, and, in some cases, rather notable effects are produced.

The theory formerly held was, that the minerals developed in the contact zone represented re-arrangement of the materials present in the country rock. Since, however, the country rock in its original form may be quite pure, as in the case of some limestones, it seems clear that many of the minerals found in the contact zone are made up of materials added from the intrusive, and this view is now quite generally held. The contact silicates formed in limestone are quite characteristic and include such minerals as garnet, epidote, wollastonite, and pyroxene.

Regional metamorphism. — Over many parts of the earth are extensive regions of rocks that have been more or less profoundly altered and which, because of great areal extent involved and the character in

[1] Contact-metamorphic deposits are occasionally developed in shales and also in quartzites.

part of changes produced, cannot be ascribed to local or contact metamorphism. A typical region of widespread and profound alteration of rocks is the crystalline province of the eastern United States, but local or contact metamorphism within this province is by no means lacking. Another area is found in the Lake Superior region, in which there occur important iron-ore deposits. The principal metamorphic rocks composing such extensive regions are gneisses, crystalline schists, slates, etc. Alteration on such an extensive scale is known as *general* or *regional metamorphism*, and applies to the reconstruction of rocks over extensive areas.

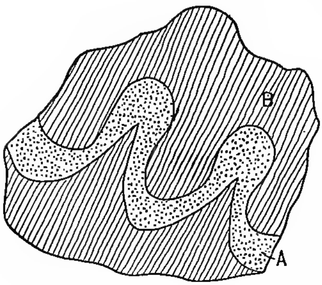


FIG. 141. — Slate showing fine cleavage lines, and layer of calcareous quartzite, showing crumpling of bedding planes. (After Dale.)

The principal effects of regional metamorphism are crystallization and recrystallization involving the formation of new minerals and the production of foliated structure, such as schistosity, gneissoid structure, slaty cleavage, etc. (discussed on pages 139, 140, 142), which result in the development of gneisses, schists, slates, etc. (See under Metamorphic Rocks in Chapter II.) Conspicuous minerals termed *metacrysts* (*pseudophenocrysts*) are frequently developed giving the rock a *pseudoporphyritic* texture. Certain ones like garnets are sometimes sufficiently abundant to make the rock of commercial value. Ordinarily the chemical composition of the rock is not much affected by regional metamorphism, although the changes may result in the loss of some substances, especially the volatile ones, and the addition of others.

Under conditions of regional metamorphism the original characters of the rocks are frequently completely obscured or destroyed, so that it becomes difficult, if not in some cases almost impossible, to state with certainty whether the original rock was a sedimentary or an igneous one. These are changes which take place at depth below the surface under conditions of deep burial in the anamorphic zone, from long and continued action of earth movements and pressure; liquids and gases, especially water; and heat, which are discussed above (pages 148, 149). The rocks are subsequently exposed at the surface through erosion, and most of those now exposed over many parts of the earth are among the older rocks of the earth's crust.

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CHAPTER IV

ROCK-WEATHERING AND SOILS

Introduction. — When exposed for a sufficient length of time to the atmosphere, all rocks undergo decay from disintegration and decomposition, and are ultimately converted superficially into a loose, incoherent mixture of sand, gravel, and clay, the upper few feet of which is called the *soil*. If the erosive action of water, wind, or ice is not too excessive, a mantle of variable thickness of decayed rock material overlies the hard and fresh rock into which it usually grades. The southern Appalachians furnish an excellent illustration of this, the rocks being very generally covered with a mantle of loose residual rock materials of variable thickness (frequently exceeding 100 feet). Frequently this loose, decayed-rock mantle must be removed before quarrying can be commenced.

The changes involved in the weathering of rocks are partly physical and partly chemical in nature, the latter representing a readjustment from unstable to stable compounds under prevailing surface conditions. The processes involved may be simple or complex, and are confined almost entirely to the belt of weathering (p. 149), which extends from the surface to the level of groundwater (Chapter VI). They are wholly atmospheric and are operative on all land surfaces above sea-level, becoming usually quite, if not entirely, inactive, at comparatively slight depths.

Importance of rock weathering. — Rock weathering is of fundamental importance from the purely scientific as well as from the economic standpoint. In the study of soils, building stone, and the superficial portions of ore-deposits, a knowledge of the principles of weathering is indispensable.

In all engineering surface projects, in the selection of stone for structural and decorative purposes, in mining and quarrying operations, and in problems of water supply, as well as in excavations of all kinds, the engineer is concerned either with the direct results of rock weathering or else its probabilities as affecting any stone used in constructional work.

Definition of weathering. — All physical and chemical changes produced in rocks, at or near the surface, by atmospheric agents, which result in more or less complete disintegration and decomposition, are

commonly grouped under the general term of *weathering*. A mechanical breakdown of the rock, called *disintegration*, results in the former breaking up into smaller particles without destroying their identity. Chemical agents destroy the identity of the mineral particles, breaking them up into new compounds, and is known as *decomposition*.

Disintegration and decomposition are usually concurrent, but for a given locality one may predominate over the other. Thus, in the arctic regions, disintegration is the dominant process by which rock masses are broken down, while in tropical regions, decomposition becomes the important process. Again, the former predominates in the arid climate of the west, while the latter is the dominant factor in the east.

Mechanical Agents

Disintegration causes the rock ultimately to crumble into fine particles of the consistency of sand and powder, which may consist of fresh mineral grains. The principal mechanical agents involved in the disintegration of rocks are (1) temperature changes, (2) mechanical abrasion, and (3) growing organisms.

Temperature changes. — The disintegration of rocks through temperature changes may result from (1) unequal expansion and contraction of the minerals, and (2) expansion caused by alternate freezing and thawing of interstitial water.

Expansion and contraction. — Most rocks are composed of an aggregate of minerals each one of which has a different rate of expansion. Unequal expansion and contraction of the individual minerals result both from diurnal and seasonal changes of temperature. In the crystalline rocks the mineral particles are crowded together closely and many of them expand unequally in different directions. When, therefore, the temperature rises the minerals crowd against each other with almost irresistible force, and when the temperature lowers they contract and draw farther apart from one another. The result of these alternating temperatures producing expansion and contraction is to weaken the rock, and cause the formation of small cracks into which water may percolate and chemical action set up, or into which roots may penetrate and further aid in disintegration.

The coefficient of cubical expansion for some of the common rock-forming minerals is given by Clarke as follows:

Quartz, 0.0000360; orthoclase, 0.0000170; hornblende, 0.0000284; calcite, 0.0000200; garnet, 0.0000250; tourmaline, 0.0000220.

Bartlett has determined experimentally the actual expansion in inches per foot for each degree Fahrenheit to be as follows for several rocks:

Granite, 0.000004825; marble, 0.000005668; sandstone, 0.000009532.

These figures indicate only a very small rate of expansion, but if continued from season to season through a long period of time, the weakening effect produced will have an appreciable bearing upon the economic importance of the stone. Such action will finally result in opening invisible cracks in the rock, or, it may be, in pulling the stone away from the mortar, which will afford ready entrance for water and thereby pave the way for decay, and final disintegration of the stone must result.

While rocks expand when heated and contract when cooled, they do not return to their original length. This slight increase in size is known as the *permanent swelling;* the permanent swelling of some 20-inch bars of stone heated and cooled through a range of temperature of 32° F. to 212° F. was: Granite, 0.004 inch; marble, 0.009 inch; limestone, 0.007 inch; and sandstone, 0.0047 inch.

An extreme case of the effect of heat on stones is seen in the destruction of buildings by fire, when many of the stones exposed to fire, or fire and water combined, are badly cracked. The expansion of stone when heated is sometimes recognized by engineers, in placing elastic joints in long walls of masonry.

FIG. 142. — Quartzite broken by temperature changes, frost and plant roots. Monroe, N. Y. (H. Ries, photo.)

Expansion due to alternate freezing and thawing. — All rocks are more or less porous and are capable of absorbing varying amounts of water. In passing from the liquid to the solid state, water expands with a force equal to about 150 tons to the square foot and about one-tenth in volume. The effects produced on rocks from the action of

continued freezing and thawing when the stone is saturated with water are much greater than from expansion and contraction through diurnal temperature changes described above.

Water gains access into rocks through the openings and spaces of various kinds. Structural planes permit a freer circulation of water than the pore spaces in the rock, and at times the water may collect in these passages more rapidly than it can be carried away, so that if the temperature lowers to the freezing point it congeals into ice, which acts as a wedge to force the walls farther apart. The freezing of water, however, in these structures in building stone, except in some stratified and foliated rocks, is usually attended with less danger than from freezing of water in the pores. The flaking off of stratified or foliated rocks by frost action is sometimes hastened by placing them in the wall of the structure on edge, with the bedding or foliation planes parallel to the exposed surface. Many buildings of our eastern cities which have been faced with brownstone (sandstone), have been injured due to this cause.

In rocks whose pores are large in size as well as straight, the water of saturation may be expelled with comparative readiness, but when the cavities are of subcapillary size the water is retained with greater tenacity; hence, the danger from freezing in the latter becomes increasingly great. Ordinarily, then, the danger from freezing of water in rocks used for constructional purposes becomes increasingly great as the pores approach those of subcapillary size.[1]

The amount of water contained in the pores of a rock at any given time depends upon the quantity of water initially absorbed, the time that has elapsed since absorption, the condition of the atmosphere, the size and shape of the pores, and the position of the stone. It is only in exceptional cases that the stone in the wall of a building is saturated (Buckley). Named in their order of importance, then, it is possible that the factors in estimating the danger from freezing and thawing are: (1) size of pore spaces, which controls the rate at which the interstitial water is expelled, (2) the amount of water contained in the pores at the time of freezing, and (3) the total amount of pore space.

Effects of frost and temperature changes. — As already explained, small cracks may be started by temperature changes, and into these as well as other fissures the frost works its way, breaking down the rock into a number of large and small angular fragments. If the rock surface is flat or gently sloping, the angular débris lies where it was formed (Fig. 142), but if the disintegration takes place on a steep hillside, or on the face of a cliff, the material falls to the bottom of the

[1] For tests of frost action on sand see Ferry, Proc. Am. Soc. Civ. Engrs., XLII, p. 1320, 1916.

slope or cliff and builds up a talus pile (Fig. 55), which in time may assume large size, and even eventually break down into a fertile soil (Fig. 143).

The much-jointed character of the rocks in some mountain regions causes frequent and dangerous rock falls, as the water freezing in them pries off large and small pieces of rock.

FIG. 143. — Talus of weathered schist, French Pyrenees. The rock has broken down to a soil which can be tilled, but has to be terraced to prevent erosion. (H. Ries, photo.)

Frost resistance tests. — When building stones are tested for frost resistance, it is customary to soak them 20 or 30 times in water under normal atmospheric pressure, and then freeze them between each soaking. Thé stone is weighed before and after the treatment in order to detect loss by weight. It has been found that, if the pores of the stone are completely filled by soaking in a vacuum, its resistance to repeated freezing and thawing is greatly decreased.

An artificial method consists in soaking the stone in a solution of sulphate of soda, and then drying it out, the theory being that the growth of the sulphate of soda crystals in the pores of the rocks exerts internal pressure. The treatment is repeated a number of times.

Carus-Wilson describes the case of a porous volcanic tuff into which sea water ascended by capillarity. On evaporating salt crystals were deposited which flaked off the stone.[1]

[1] Nature, CVIII, p. 66, 1918.

Quarry water. — Many stones, especially stratified ones, contain water in their pores when first quarried. This is known as quarry water, and may be present in some stratified rocks, as sandstones or porous limestones, in such quantity as to interfere with quarrying during freezing weather.

Mechanical abrasion. — Mechanical abrasion is one of the most important agents in the disintegration of rock masses. It is accomplished mainly by wind and running water working concurrently with other agents of disintegration.

In many parts of the world, the wind does considerable work in removing the fine-grained products of rock decay or other sandy deposits. Not only does it remove this loose material, but often drives it with such force against rock surfaces as to wear them down by mechanical abrasion. The etching and engraving of glass by artificial sand blasts well illustrates the nature and potency of this agent. Many authors have recorded the work wrought by this agent.

FIG. 144. — Granite boulders produced mainly by disintegration in an arid climate. Winchester, Cal. (H. Ries, photo.)

The work accomplished by this agent is naturally most effective in arid regions, which are generally characterized by an almost total absence of vegetation. Its effects, however, are oftentimes present in our humid Atlantic coast climate, where the beach sands are caught up and driven with much violence before the wind. In the case of one of the light-houses on Cape Cod, the impact of the wind-driven sand was so great on the heavy glass in the windows as to render some of them no longer transparent, and necessitating their removal in a few instances.

Naturally the action resulting from wind abrasion is a very slow one, but, after long lapses of time, and under constant blast, the effects are manifest.

Abrasion of building stones. — While building stones may be subject to abrasion by wind-blown sand as noted above, a much more frequent cause of this type of wear is the rubbing action they are exposed to when used in pavements, steps, stair treads, or flooring. Here the grinding action produced by sand being constantly rubbed back and forth on them often causes a noticeable amount of wear which few stones are able to resist. Marbles, for example, show great variation in this respect, and when different kinds are used in the same floor to produce color patterns, the floor if subjected to much foot traffic may wear uneven in a remarkably short time. The floor of the Union Station in Washington, D. C., affords an excellent example of uneven wear.

The abrasive resistance of a stone may be tested by laying it on a rubbing table, weighting it down, and applying emery or some other abrasive at a given rate while the table revolves.

Growing organisms. — Both plants and animals aid to some extent in the breaking down of rock masses, through action that is partly physical and partly chemical. While they are not usually the principal agents involved in the processes of rock decay, yet they become at times important factors in such destruction. The chemical action resulting from these organisms is mainly that of deoxidation and solution.

An important function of plant growth is the retention of moisture, whereby the rock-surfaces are kept constantly damp, and thus solvent action by the water is promoted. Similarly chemical decay among rocks is promoted by the formation of vegetable mould (humus) derived from the decay of plants, by the retention of moisture, by furnishing carbon dioxide to the water, and by a leaching process which is reducing in action.

The physical action by plants is shown by the penetration of their roots into cracks and crevices, which wedge apart the rock, and at times dislodge varying sized fragments from the parent ledges. It may result in partial detachment of parts of the masonry from walls of buildings and other structures, where creeping vines are allowed to cover the structure.

Plant growth may also exercise a protective action. Where vegetation is abundant, the erosive action of wind and rain is retarded. Such protective influence is well shown in reclaiming lands over parts of France.

Chemical Agents

The chemical processes of weathering are of both scientific interest and practical importance. The changes that take place in many building stones and some of which may work injury to them, are often of a chemical nature. Chemical processes often play an important rôle in the softening of rocks underground. In ore deposits chemical

weathering is of widespread importance (Chapter XII, and as a result of it many ores are enriched and made workable). No less important is chemical weathering to the agriculturist, for it breaks down the mineral compounds in the soil and renders certain elements more available for plant nourishment.

Moisture is of course important as an agent of chemical decay, and acts indirectly in serving as a carrier of certain gases and acids which it brings in contact with the minerals that are decomposed.

Normal atmospheric air consists chiefly of a mechanical mixture of nitrogen and oxygen in the proportion of four volumes of nitrogen to one of oxygen. In addition to these, there are usually present small quantities of other substances, chief among which are water vapor and carbon dioxide. Of these oxygen, carbon dioxide and water are much the most important chemically active compounds, the most abundant constituent nitrogen being chemically inactive under normal atmospheric conditions. The rain or moisture of the atmosphere brings the oxygen and carbon dioxide into contact with the rocks.

Besides the gaseous solutions of oxygen and carbon dioxide, the water solutions usually contain variable amounts of different substances, especially the carbonates of the alkalies and the alkali earths, and acids, such as hydrochloric, sulphuric, nitric, etc., which are active agents in decomposing rocks.

The most important chemical reactions that take place in the belt of weathering as the result of the action of various agents are: (1) Hydration, (2) oxidation, (3) carbonation, and (4) solution. These are discussed below in the order named.

Hydration. — Hydration is the process by which certain minerals take up water in chemical combination, the resulting compounds being hydrous minerals. A simple case of hydration is represented by the change of anhydrite to gypsum when the former is exposed to water, as shown by the equation:

$$\underset{\text{(Anhydrite)}}{CaSO_4} + \underset{\text{(Water)}}{2\,H_2O} = \underset{\text{(Gypsum)}}{CaSO_4 \cdot 2\,H_2O}.$$

Among the important hydrous minerals formed are many silicates, such as kaolin, serpentine, talc, chlorite, zeolites, etc.; oxides, especially those of iron and aluminum, such as goethite, turgite, and limonite, diaspore and gibbsite; and of the sulphates, gypsum. The water for hydration is derived chiefly from the atmosphere and the reaction is one of the most extensive and important that takes place in the belt of weathering.

By comparing analyses of fresh and decayed rock, it will be found that an increase in water invariably occurs, the amount of water

increasing with the stage of decay. In rock decomposition, therefore, hydration is one of the main factors, and, when not accompanied by a loss of constituents through solution, it involves expansion of volume and great liberation of heat, becoming thereby a physical agent of decay. In simple hydration the volume increase ranges from a very small per cent to as high as 160 per cent, but commonly the increase in volume is less than 50 per cent (Van Hise).

Although hydration involves increase of volume, the rocks so affected do not always have room to expand. Engineers engaged in tunneling have sometimes noticed that apparently fresh rock when brought to the surface crumbles rapidly. This is because the rock, whose minerals are partly or wholly hydrated, was under strain while in the ground, and therefore disintegrates rapidly when released. This slaking has been observed by Merrill in the granites of the District of Columbia and by Derby in sedimentary rocks in the railway cuttings of Brazil. Hydration caused by percolating water may at times cause swelling and heaving ground in tunnels or mines.

Dehydration, the opposite reaction of hydration, while not recognized as an important process in weathering, may take place in regions of high temperature, such as in some of the surface hydrous iron compounds of the southern Appalachian soils.

Oxidation. — Oxidation is promoted by the presence of moisture and is usually accompanied by hydration. All rocks which carry iron in the form of sulphide (pyrite, marcasite, and pyrrhotite) and as ferrous iron in many silicates (pyroxene, amphibole, micas, and olivine) and carbonates, are oxidized in the belt of weathering. The process is also of great importance in the surface alteration of ore-deposits (Chapter XII).

The two following equations represent oxidation, and the second one in addition involves hydration:

$$FeS_2 + 7\,O + H_2O = FeSO_4 + H_2SO_4$$
$$6\,FeSO_4 + 3\,O + 3\,H_2O = 2\,Fe_2(SO_4)_3 + 2\,Fe(OH)_3.$$

The principal cause of weathering in these cases is largely the affinity of iron in the ferrous state for oxygen, which finally results in chemical combination of the two, forming hydrated ferric oxide. The bright red and yellow colors of the residual products of rocks containing these minerals are due to the formation of iron oxides by oxidation. The red and yellow soils derived from the deeply-weathered crystalline rocks of the Piedmont province in the southern Appalachians furnish an excellent illustration of the oxidation of iron compounds to hydrated ferric oxide. The early stages of oxidation

accompanied by hydration may frequently be observed in the "sap" portions of granite and other siliceous crystalline rocks used for building stone containing biotite or other ferromagnesian minerals, in the slight discoloration from liberated iron oxide of the iron-bearing minerals.

Another frequent and familiar example of oxidation is that of the iron sulphides (pyrite, etc.), which are common constituents of many rocks. The iron becomes oxidized to the hydrated sesquioxide form with the liberation of sulph-acids which may also aid in breaking down the rocks. The first stage in the oxidation of the sulphides is the formation of sulphates according to the chemical equation on page 162. When formed in building stones, these sulphates sometimes cause an unsightly scum on the surface of the building.

When these soluble sulphates crystallize in the pores of the stone near the surface, they sometimes cause scaling and chipping. The formation of sulphates in stone is not always due to the decay of sulphides, but at times may be due to sulphuric acid in the air being carried by moisture to a rock containing carbonates either as component minerals or interstitial cements, which by contact with the acid are converted into sulphates. This action is not unknown in localities where acid fumes are discharged into the atmosphere by the stacks of factories, smelters, etc.

Oxidation may be accompanied by either decrease or increase in volume. Probably decrease in volume usually attends the oxidation of carbonates and sulphides, but oxidation of silicates not involving a loss from solution may be accompanied by increase in volume.

The oxidation of sulphides is a most important process in the weathering of many ore-deposits. (See secondary enrichment, p. 335.)

Deoxidation. — Deoxidation, the reverse of oxidation, is a less frequent reaction in the belt of weathering than oxidation. When carrying organic matter in solution water becomes a reducing agent, and ferric iron is reduced to the ferrous state, which in the presence of carbon dioxide unites to form ferrous carbonate (siderite). From this source and by this process ferrous carbonate may be derived for the material of chalybeate (iron) springs, and the iron-carbonate deposits (black-band ore and clay ironstone) so often associated with coal beds. Frequent illustration of the reaction is found in the bleaching of red soils to gray or white ones, and in the local bleaching of some ferruginous sands and sandstones. By a similar process ferrous sulphates may be converted into sulphides.

Carbonation. — Carbonation, or the chemical union of carbonic acid with bases to form carbonates, is a dominant weathering process. It consists chiefly in the substitution of carbonic for silicic acid in the silicates.

It has been demonstrated experimentally that carbon dioxide in aqueous solution attacks many minerals, such as the feldspars, hornblende, olivine, serpentine, muscovite, biotite,[1] etc., among the silicates, under ordinary conditions of temperature and pressure. The carbonates of the alkalies and the alkali-earth metals formed are removed in solution. They have the power of decomposing many silicates and hence may become important agents in the further breaking down of these minerals.

The following common reaction showing the decomposition of orthoclase involves carbonation as well as hydration:

$$\underset{\text{Orthoclase}}{K_2O.Al_2O_3.6\,SiO_2} + 2\,H_2O + CO_2 = \underset{\text{Kaolinite}}{Al_2O_3.2\,SiO_2.2\,H_2O} + K_2CO_3 + 4\,SiO_2.$$

The source of carbon dioxide for the process of carbonation in the belt of weathering is derived partly from the atmosphere in which it is present in amount equal to about 0.045 per cent by weight, and partly by oxidation of organic materials (plants and animals) on the surface by bacteria and oxygen. Other less important sources are known.

The process of carbonation in silicates, the negative side of which is *desilication*, is accompanied by the liberation of silica, which may remain as quartz, or be removed in solution as a colloid. It has been observed that when plant growth is abundant, as in the tropical regions, the amount of dissolved silica in the underground waters is larger than in regions where vegetation is scant or lacking.

This process which yields a hydrous clay-like material low in silica is known as *laterization*, and the product is *laterite*. The bauxite deposits of Arkansas, the iron and nickel ore-bearing clays of Cuba, and the nickel ore-bearing clays of New Caledonia are of this type.

Carbonation may take place without other reactions, but it is usually accompanied either by hydration or by hydration and oxidation. In either case the process is accompanied by an increase in volume.

Solution. — Concurrent with and promoted by the chemical processes of oxidation, carbonation, and hydration, described above, much mineral matter is taken into solution by the underground waters in the belt of weathering. The dominant processes, carbonation and hydration, render the compounds more soluble, while the change from ferrous to ferric iron by oxidation has the opposite effect.

The rocks most readily affected by solution are the carbonates, as limestones and dolomites, and in the former, especially, solution sometimes goes on actively along joint and stratification planes (Fig. 145) (Chapter VI). Gypsum is also attacked, but not as readily as limestone.

This dissolved mineral matter in the belt of weathering may be disposed of in one of several ways: (1) It may be delivered in part to the oceans by means of surface streams, (2) much of it may be carried lower down by the downward percolating waters into the belt of cementation and there precipitated and deposited, and (3) it may be

[1] The presence of carbon dioxide in water is not always necessary to cause decay of these minerals.

partly precipitated in the belt of weathering as in the formation of cave deposits, and those of the oxides of iron, aluminum, and manganese. The process of secondary enrichment of such importance in many ore-deposits (Chapter XII) is a phase of this process.

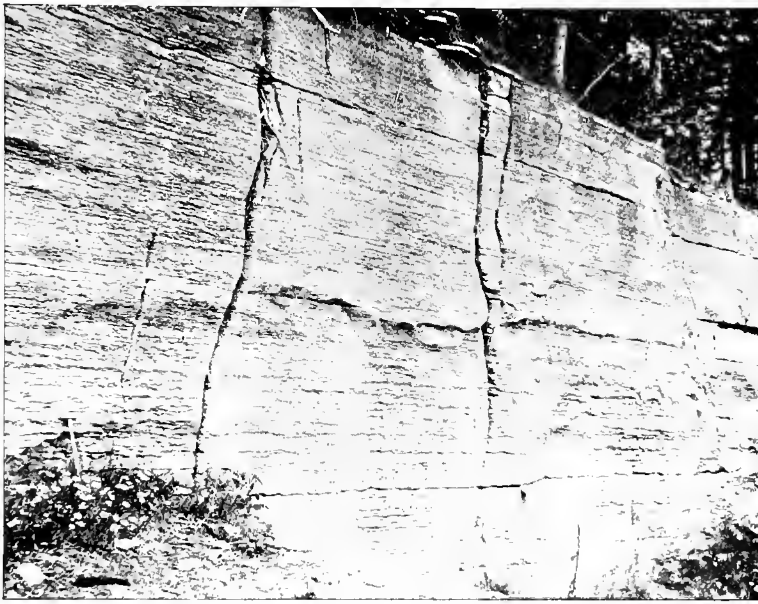

FIG. 145. — View in a limestone quarry showing solvent action of water along joint planes. (H. Ries, photo.)

Only a very few minerals are readily soluble in pure water, but chemically-pure water does not exist in nature, and when carrying in solution certain materials, such as carbon dioxide, organic matter, etc., the solvent power of water is greatly increased.

In order that some idea may be had of the total amount of solids removed in solution by some of the larger rivers the following table taken from Russell may be cited (see further under Chapter V):

	Tons per year
Rhine	5,816,805
Rhone	8,290,464
Danube	22,521,434
Thames	613,930
Nile	16,950,000
Croton	66,795
Hudson	438,000
Mississippi	112,832,171

About one half of the dissolved load is lime carbonate.

The cementing material of some sandstones (calcareous) is dissolved by atmospheric water, causing the rock to crumble into loose sand. On the other hand, the calcium carbonate of some impure limestones becomes so completely removed by solution, that only a porous skeleton of clayey and siliceous impurities is left. The *rottenstone* used for polishing purposes is an example of this.

Solution is also an important process in ore deposits for the reason that (1) in some cases it removes worthless material leaving the ore minerals behind, and (2) it may remove ore minerals and add them to those lower down in the deposit. In either case it results in enrichment of the deposit.

Fig. 146. — Weathered outcrop of silicified limestone conglomerate. The silicified pebbles and quartz veins are more resistant. (G. van Ingen, photo.)

The weathering of rocks by solution begins at the surface and also penetrates the rock along joint planes (Figs. 145, and 146).

Summary of chemical decay. — A study of the chemical changes involved in the weathering of siliceous crystalline rocks, by comparing analyses in the usual way of the fresh and correspondingly decayed rock, as shown by Merrill from his own work and that of others, may be summarized as follows:

1. Hydration is an important factor, the quantity of water increasing as the stage of decomposition advances, and in the early stages of weathering it may be the most important factor.

2. The formation of ferric oxide retained as a pigment in the insoluble residual rock decay through oxidation of ferrous compounds.

3. There is in every case a loss in silica, a greater proportional loss in lime, magnesia, and the alkalies (soda and potash), and a proportional increase in alumina and sometimes iron oxide, resulting on the whole in a decided loss of materials through solution.

4. So far as is indicated by available analyses the total loss of constituents in siliceous crystalline rocks seldom exceeds 60 per cent for the entire rock. In calcareous rocks the loss through solution may amount to 99 per cent in extreme cases.

Analyses of Fresh Rocks and Residual Clays

Constituents.	Gneiss.[1]		Diabase.[2]		Limestone.[3]	
	Fresh.	Decomposed.	Fresh.	Decomposed.	Fresh.	Decomposed.
SiO_2	60.69	45.31	47.90	41.60	7.41	57.57
Al_2O_3	16.89	26.55	15.60	37.20	1.91	20.44
Fe_2O_3	9.06	12.18	3.69	3.21	0.98	7.93
FeO			8.41	0.30		
CaO	4.44	......	9.99	0.23	28.29	0.51
MgO	1.06	0.40	8.11	0.02	18.17	1.21
K_2O	4.25	1.10	0.23	......	1.08	4.91
Na_2O	2.82	0.22	2.05	0.07	0.09	0.23
CO_2	......	......	....	......	41.57	0.38
P_2O_5	0.25	0.47	....	......	0.03	0.10
Loss on ignition	0.62	13.75	H_2O 2.34	13.54	H_2O 0.57	6.69

[1] From Virginia, G. P. Merrill. [2] Penokee district, Mich., Irving and Van Hise. [3] J. S. Diller, authority.

Residual clay and sand. — As a result of rocks being broken down by weathering there forms, as already stated, a mantle of incoherent material, which if clayey in nature is termed *residual clay;* if sandy, *residual sand.* If decomposition has been active the product is usually clayey, but if disintegration has been the dominant weathering agent, a sandy material is more likely to result.

The analyses above give the composition of three fresh rocks and the residual clays derived from them, but it should be pointed out that one cannot always tell from the composition of the clay, what the parent rock was.

Uses of residual clays. — Residual clays are widely used in the manufacture of clay products. The iron-stained ones are employed in brick and tile manufacture. The white ones, known as *kaolins,* and derived by the weathering of rocks free from iron-bearing minerals, are of value in the manufacture of china, white tile, refractory products, and Portland cement. Kaolins are worked in North Carolina, Pennsylvania, and Maryland.

Where the parent rock contains metallic compounds, these sometimes become concentrated in the residual clay, from which they can be separated by washing. Examples of this are the residual iron, manganese, and zinc ores worked in the Southern States.

Mineral resistance. — All minerals do not show the same degree of resistance to weathering agents; therefore, other things being equal, that rock will yield most readily which contains the greater quantity of less resistant minerals. Sulphides yield more readily than carbonates and these in turn weather more easily than silicates.

Relation of Structure to Weathering

The depth and extent to which weathering affects different rocks will depend on whether they are porous or dense, massive foliated, or fractured. Thus a rock might be weathered to a depth of 50 feet at one point and 500 feet at another, due to the difference in depth to which fractures extend.

Any weak spots in a rock weather back more readily than others. In many limestones, we find layers of siliceous or clayey impurities interbedded with the more highly calcareous ones. When the surface waters find their way down joints, or over the surface, the more soluble portions are dissolved, while the impure ones, being less soluble, remain in relief (Fig. 146).

In tunneling and mining, streaks of soft, weathered rock are sometimes met. These, in some cases, represent weathering of the rock along some fissure, or in other instances they may be weathered dikes which have been less resistant than the wall rock (Chapter II).

On the surface the position of an ore vein or dike may be represented by a trench or a ridge, depending on whether it is more or less resistant than the country rock.

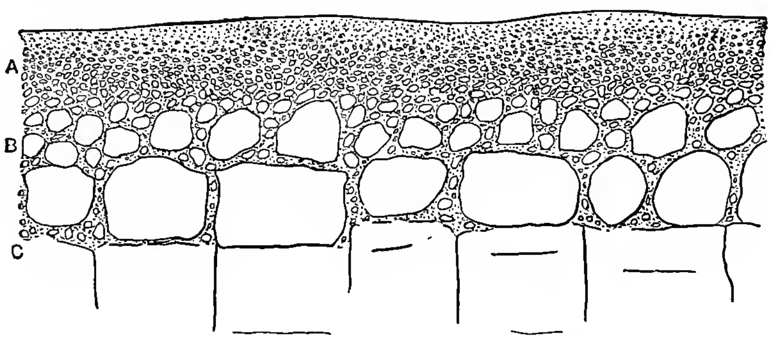

FIG. 147. — Section showing formation of residual clay from granite. (A) residual clay; (B) zone of clay and partly decayed rock fragments; (C) unweathered granite.

Weathering of Siliceous Crystalline Rocks

Igneous rocks like granite suffer most in the early stages of weathering from disintegration, although often accompanied by some chemical action, especially hydration. This has ample verification in the very small percentage of clay in the partially weathered product and its slight discoloration by iron oxides set free through oxidation. The incipient stage of weathering of feldspathic rocks is usually

shown in the chalky appearance of the feldspars, due to kaolinization from hydration. The amount of water increases rapidly as decomposition advances.

In the more advanced stages of weathering, carbonation, oxidation, and solution become the dominant processes, and as a result the rock is finally reduced to sand and clay, more or less discolored by iron oxides set free through decomposition of iron-bearing minerals, such as biotite, hornblende, etc.

Fig. 148. — Granite boulders produced by weathering. The material surrounding them is decomposed rock. (T. L. Watson, photo.)

The joints in massive igneous rocks are easy lines for the percolation of surface waters, that (Fig. 148) produce decay of the rock, extending inward from the joint surfaces.

An interesting form of weathering frequently observed in igneous rocks is illustrated in Fig. 150, which shows granite and diabase boulders consisting peripherally of concentric shells, which break off one after another in passing from the surface towards the center. This form of weathering has resulted from the more rapid decay on the edges and corners than on the flat sides of the jointed blocks, the blocks being gradually rounded and formed into boulder-like masses of varying size. (Fig. 148.)

In the advanced stage of weathering (decomposition) of metamorphic foliated rocks, such as gneiss and schist, the original structure of the fresh rock is frequently preserved in the decayed product (Fig. 149).

Weathering of Sedimentary Rocks

The sedimentary rocks, such as sandstones, shales, and argillites, composed of the weathered products of preëxisting rocks weather through processes that are largely mechanical, while the purely calcareous rocks weather through solution.

Sandstones. — Sandstones vary greatly both in texture and degree of compactness, as well as in composition and cementing material.

Those containing calcareous and ferruginous cements usually crumble to sand through solution of the cement by atmospheric waters, while

Fig. 149. — Residual clay derived from gneiss. The banded structure of parent rock is preserved, and dips to the right. The vertical grooves are pick marks. (T. L. Watson, photo.)

those sandstones whose bond is silica are refractory to chemical agents and weather by disintegration. Porous sandstones may suffer greatly

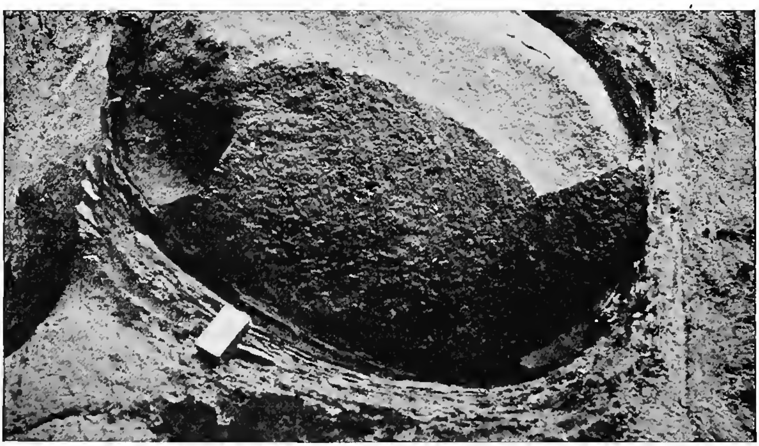

Fig. 150. — Diabase showing boulder produced by weathering, surrounded by concentric shells of decayed rock. (T. L. Watson, photo.)

from frost action in climates where freezing temperatures are reached. "It is to their great absorption power that is due the large amount of

disintegration and foliation seen in the softer sandstones, as the Triassic of the eastern United States and the sub-Carboniferous of Ohio." (Merrill.)

Shales and slates. — These are indurated rocks, which, with the exception of the calcareous varieties, break down from weathering largely through physical processes (Fig. 151). They yield clays which differ from the original rock chiefly in the degree of hydration and the state of oxidation of the iron. The first physical indication of decay is often shown by a softening of the rock.

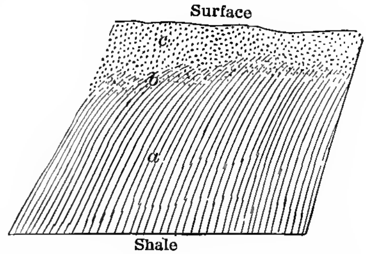

Fig. 151. — Section showing residual clay derived from shale. *a* shale; *c* clay.

Limestones and dolomites. — The calcareous rocks weather almost entirely through solution effect, for they possess a minimum capacity for absorbing water, and are, therefore, liable to little or no injury from freezing. Thus in vertical sections of limestone and its overlying mantle of residual decay, the two are sharply defined from each other (Fig. 152, which compare with Fig. 147). In some districts the limestone residual clay contains limonite nodules, and when removed to

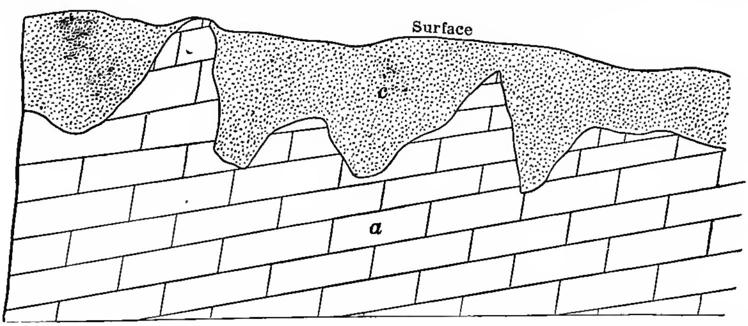

Fig. 152. — Section showing residual clay derived from limestone. Note the sharp line of contact between clay and parent rock, as well as irregular surface of latter.

obtain these, the underlying limestone exhibits a curious but characteristic pinnacled surface (Fig. 153). The solvent action of water is noticed on some gravestones made of limestone, in which the inscriptions are rendered illegible in many cases within a short period of years. The coarse crystalline varieties, especially dolomite, may weather through granulation.

Gypsum. — Like limestone, gypsum is soluble in surface waters, but not as readily. The weathered surface of a gypsum deposit may

therefore show the same pinnacled structure and underground solution channels as are found in limestone areas.[1] If anhydrite is present, it will, under the influence of surface waters, alter to gypsum, the change being accompanied by an increase in volume. In some gypsum quarries, solution channels, filled with residual clay and surface dirt, have occasionally been mistaken for fault zones by the quarrymen.

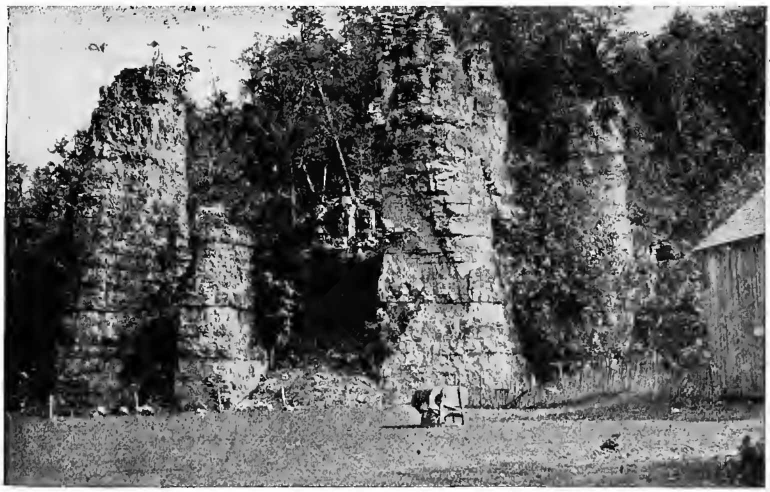

FIG. 153. — Limestone "chimneys," separated by hollows caused by solution along vertical joint planes. (T. L. Watson, photo.)

Soils

The soil may be considered as the superficial, unconsolidated mantle of weathered rock material, which, when acted upon by organic agencies, and mixed with varying amounts of organic matter, may furnish conditions necessary for the growth of plants (Coffey). The less soluble portions of the rock remain, under conditions of weathering, to form the mantle of unconsolidated rock material, the superficial portion of which may support plant life and is ordinarily mixed with a small amount of organic matter (humus). Some soils may be formed largely through the action of physical agents when little or no loss through solution may be shown.

While all soils have been derived from the disintegration and decomposition of rocks, it must be understood that not all of them have been formed from weathering of the rocks which they overlie. On the contrary, there are large areas of soils which owe their origin not to the decay of the underlying rocks, but represent the transported and deposited products of rock decay by either water, wind, or glacial ice. In other words the weathered rock material formed in one locality and from a given kind of rock may be removed from the place of formation and deposited in another locality of wholly different rock. As a result of transportation, the materials from

[1] For caves in gypsum see, for example, Okla. Geol. Survey, Bull. 11, 1913.

many different kinds of rocks become mixed and the soils are both heterogeneous and complex as to mineral composition.

According to whether soils have been formed in place, or have been removed from their original place of formation, we may group them into (1) *residual* soils, and (2) *transported* soils. These may be further subdivided on the basis of the agencies involved in transportation or original formation.

Residual soils. — These include all deposits derived by the processes of rock-weathering or from organic accumulation in place. They include (1) *residual* deposits, derived from the decay of the immediately underlying rocks; and (2) *cumulose* deposits, which have formed in place from the accumulation of organic matter with ordinarily small amounts of rock waste, such as many of the peat and muck deposits in ponds and lakes.

Transported soils. — These may be grouped into (1) colluvial, (2) alluvial, (3) æolian, and (4) glacial, according to the agent involved in transportation. Colluvial deposits include the heterogeneous masses of rock waste resulting from the transporting action of gravity, such as talus, cliff, and avalanche accumulations, etc. Alluvial deposits have been formed through the agency of running water, and are usually well assorted, and therefore bedded or stratified. Æolian deposits owe their origin to wind action, while the glacial deposits are the result mainly of ice action with or without that of water (Chapter X).

According to texture, soils may be divided into sand, sandy loam, loam, clay loam, and clay. A loam is usually defined as a mixture of sand or clay with some organic matter.

Composition of soils. — Soils are composed of mineral and organic matter, with usually the former predominating, although some peat and muck soils may contain as much as 75 per cent or more of organic matter. Probably the average in organic matter in most soils is less than 3 or 4 per cent.

Soils contain a variety of minerals, and any mineral commonly occurring in rocks may be found in soils. Silica in the form of free quartz and various silicates, alumina as hydrous silicates, and iron as hydrated oxides, make up from 80 per cent to 90 per cent of the superficial portions of most deposits (Merrill). New minerals may be formed. Muck and peat, marsh and swamp, and meadow types of soils are characterized by unusually large percentages of organic matter.

References on Rock Weathering and Soils

1. Buckman, H. O., Chemical and Physical Processes involved in Formation of Residual Clay, Trans. Amer. Ceramic Society, XIII, p. 336, 1911. 2. Hilgard, E. W., Soils, (The Macmillan Company), N. Y., 1907, 593 pages. 3. Merrill, G. P., Rocks, Rock-Weathering, and Soils, (The Macmillan Co.), N. Y., 1906, 400 pages. 4. Van Hise, C. R., A Treatise on Metamorphism, Mon. XLVII, U. S. Geol. Survey, 1904, 1286 pages.

For soils, see the publications of the Bureau of Soils, U. S. Dept. of Agriculture, Washington, D. C., and of the various State Agricultural Experiment Stations.

CHAPTER V

DEVELOPMENT, WORK AND CONTROL OF RIVERS

Introduction. — The work of rivers past or present has to be considered in many branches of engineering work. Hence the engineer should be familiar not only with many phases of the work of running water, but especially with the deposits that have been built by streams.

River improvement for navigation, surface water supply, hydro-electric power plants, railroad construction, and irrigation are all connected with or affected by the surface flow of water as will be presently explained.

The nature of the valley bottom, character of banks, and permanence of channel need also to be considered in connection with road construction, bridge foundations, and docks.

The rain water which falls on the surface is disposed of in part by: (1) evaporation; (2) absorption by soil; and (3) surface run-off. The last of these gathers together to form streams, often of navigable size. These streams which are of varying volume, velocity, and size are active agents of erosion; they carry away more or less of the eroded material, and deposit it again under favorable conditions.

To discuss in a theoretic manner the way in which streams perform their work may be of scientific interest, but unless their bearing on engineering work is stated, the discussion loses much of its practical significance.

Stream Flow

Rainfall. — The amount of rain which normally falls in any given region varies in different parts of the country.

Few areas of the United States are entirely free from rainfall, but the average varies considerably as shown on the map, Fig. 154.

Evaporation. — This is small while precipitation is going on, but if water or snow remains on the surface, much of it may evaporate especially in clear, dry weather. However, the proportion of rainfall that returns to the air by evaporation varies greatly under different conditions, and will be affected by temperature, wind velocity, character of vegetation, and nature of soil.

It is less in a cool climate with light breezes than in a hot one with

strong winds. It goes on more rapidly in cleared areas than in forested ones, and is greater from clayey than from sandy soils.

In the Virginia Coastal Plain, for example, evaporation amounts to more than 50 per cent of the rainfall.

Run-off. — The term *run-off* includes that portion of the rainfall which flows away on the surface in the form of visible streams. Only a small portion of the rain is directly disposed of in this manner, for even though the volume of a stream is large, much of the water in it may have first soaked into the ground, and then rejoined the river by seepage from its banks.

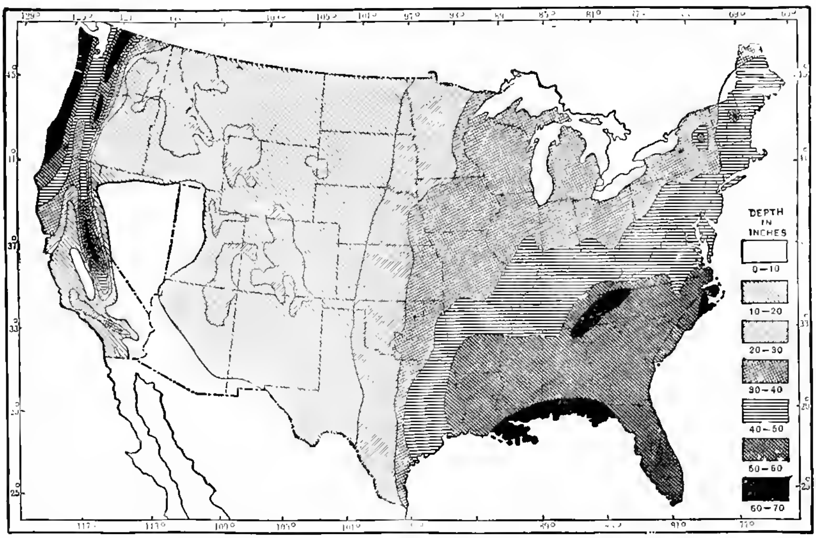

FIG. 154. — Map showing mean annual rainfall of the United States. (After Fuller, Domestic Water Supplies.)

Vegetation and temperature seem to be the chief factors controlling run-off, as has been shown by Hoyt [1] who demonstrated that the winter run-off in Vermont is 92 per cent of the rainfall, and in Virginia 63 per cent, but that the summer run-off is practically the same for the two states.

Factors controlling run-off. — The amount of run-off is affected by: (1) Amount and intensity of precipitation; (2) slope; (3) character and condition of soil; (4) vegetation; and (5) wind. The effects of these factors are as follows:

1. A heavy shower may give an abundant run-off, but a light one may be absorbed to a considerable extent by the soil, before much

[1] Trans. Amer. Soc. Civ. Eng., LIX, p. 431.

run-off takes place. A steady rain will increase the run-off because in such event the soil, unless very dry and porous, becomes so saturated that it cannot absorb any more water, and the entire precipitation finds its way to the streams. So too, if a given quantity of rain falls in a short time, more of it will run off, than if the same amount were precipitated slowly, and the soil had a better chance to absorb it. A frozen soil may exert a similar effect. Again, if a warm rain falls on snow, the latter not only prevents its filtering into the soil, but the melting of the snow adds to the volume of the streams. Melting snows are said to rarely affect large streams, but the same is not true of smaller ones, especially in hilly or mountainous regions.

2. Water will drain off more rapidly on a steep slope than on a gentle one. Newell states that a rainfall giving as high as 30 to 40 per cent run-off on the steep sides of a mountain range may not produce more than 3 or 4 per cent on the lower levels or gently rolling plains.

3. Porous soils absorb more rain than dense ones, but even a porous one which is water soaked or frozen will permit rapid surface drainage.

4. Vegetation, especially forest growth, is a strong deterrent of the surface drainage, and exerts a beneficial effect, because it retains the moisture and feeds it more slowly to the streams.[1] Where forests have been removed from the watershed of a river, or the vegetation destroyed in other ways, as by mining, smelter fumes, etc., the rainfall drains off rapidly, and the stream may be subject to great fluctuation.

5. Much of the water which remains on the surface escapes by evaporation, but the rate of this is influenced by several factors such as the dryness of the atmosphere, temperature, and vegetation. For example in Owens Valley, California, measurements made on streams flowing from the mountain slopes to the valley floor, show that they lost considerable water by evaporation due to the warm dry atmosphere.[2]

Ratio of run-off to rainfall. — For many purposes, irrigation in particular, it is desirable to know the ratio of run-off to rainfall, but unfortunately no rule can be made to apply to all parts of the country.

On some watersheds[3] of the eastern and more humid regions of the United States, having a rainfall which is relatively constant in quantity and time, there appears to be a somewhat consistent ratio between rainfall and run-off, but in the arid west no such constant ratio appears to exist.

[1] Chittenden, H. H., Relation of forests to stream flow. Trans. Amer. Soc. Civ. Engrs., 1908, and Eng. News, Oct., 1908.

[2] Lee, U. S. Geol. Surv., Water Sup., Pap. 181, 1906.

[3] A *watershed* of a stream includes all the area whose drainage runs into that stream.

Discharge of Various Rivers

River.	Discharge in cubic feet per second. Minimum.	Maximum.	Annual mean.	Ratio of minimum to maximum.	Extreme range between high and low water.	Remarks.
Columbia	48,500	1,390,000	67,000	1 to 28.7	....	Measured at Dalles.
Mississippi at St. Paul	1,500	117,000	......	1 to 23.4	19.7	
Mississippi at St. Louis	30,000	1,200,000	225,000	1 to 40 0	42 5	
Mississippi at Cairo	45,000	1,507,000	....	1 to 33.5	54.0	
Mississippi at Vicksburg	....	1,617,000	....	....	52.5	
Mississippi at New Orleans	65,000	1,740,000	....	1 to 26.8	21 4	
Missouri at Sioux City	7,000	650,000	....	1 to 92.8	19.0	
Missouri at mouth	15,000	900,000	100,000	1 to 60.0	35.0	
Niagara	175,000	260,000	219,850	1 to 1 49	....	
Ohio at Pittsburgh	1,400	439,000	....	1 to 313.5	35.6	
Ohio, just below Kanawha River	5,600	....	....	....	63 5	
Ohio, just below Kentucky River	6,900	....	....	....	59.4	
Rio Grande at El Paso	....	16,600	1,500	....	....	In dry seasons flow all subsurface.
St. Lawrence	185,000	330,000	251,900	1 to 1.78	....	
Tennessee at Chattanooga	3,700	468,000	....	1 to 126	58.6	

In comparing the *run-off* from different watersheds, all the influencing factors must be considered, otherwise serious errors may result. If deductions are to be made from such comparisons, it is important not only to compare areas showing similar conditions, but having approximately the same size. Such deductions cannot take the place of direct measurements.

Stream formation. — As the rain falls on the surface, that portion which runs off becomes rapidly concentrated along definite lines due to inequalities of the surface, thus developing a series of rivulets, which in turn converge to form brooks, and these join to form large streams or rivers. The total quantity of water conveyed to the sea is very large, it being estimated that rivers carry about 6500 cubic miles of water to the ocean annually.

This is conveyed by rivers of varying size and length. Streams are not only more numerous in regions of abundant rainfall, but have a larger number of branches.

Rivers may be divided into three classes according to the degree of continuity of their flow. These are: (1) *permanent* or *perennial streams,* which flow throughout the year, receiving their supply of water largely from rain and springs. The surface of groundwater in adjacent regions usually stands higher than the stream bed; (2) *temporary* or *intermittent streams,* which flow during only a part of the year. Many of those in arid regions are of this latter class, and they are supplied directly by surface run-off, many flowing only during the rainy season; (3) *interrupted streams,* which flow on the surface only in portions of their course, the water flowing along underground in gravels, sands, or rock channels especially in limestones in the inter-

vening stretches. The Rio Grande River of New Mexico and Texas is of this type. Similar ones are not uncommon in some limestone areas. Each type of stream performs similar work, but that done by it differs in degree and constancy.

Rivers may also be separated into two groups according to the character of the material forming the channel. These are: (1) *Rock-walled channels* and (2) *alluvial channels*. The former are relatively permanent, characteristic of rivers of steep slope, and common in mountain regions. The latter are cut in soft material, the channel is of changeable character, and may shift with every flood.

The water which is held by the soil and slowly drained into the streams is of great benefit to navigation, since it keeps up the supply at a time when there may be little or no surface run-off. One large river with its tributaries may therefore drain a very large area, which is called its *basin*.

While streams may fluctuate in the volume of their flow, the variations produced by fluctuations in the supply of spring water are not as great or as sudden as those produced by rains or melting snow.

Whatever the size of a river, its behavior is governed by certain laws, so that either a large or a small stream may exhibit the same sinuosities, bars, eddies, or floods.

In the case of navigable rivers, it is necessary to maintain a free, unobstructed channel, and since much of the work done by the stream current is injurious to the permanence of such conditions, it is of the highest importance for an engineer engaged in river improvement to understand how river currents work, so that if necessary he can control and regulate them. Indeed, the work of river improvement is one of the most important branches of civil engineering.

Measurement of water. — This may be done with two different objects in view: (1) measurement of supply, and (2) measurement of duty requirement.

"Measurement of supply is for the purpose of determining the quantity of water available for irrigation, power development, and domestic uses. It includes the measurement of run-off from the various streams and to a limited degree also the determination of underground flow which may be made available for use through pumping or artesian flow. Measurement of duty requirement includes the determination of the amount used for irrigation, power development, and other purposes. Both of the above classes of measurements are necessary in an enterprise involving the use of water; the first to determine the amount available and the second to determine the extent of an enterprise which a given supply will furnish." (Newell and Murphy.)

Stream measurement. — The *discharge* of a stream is the amount of water which it carries, and the determination of this amount is known as *gaging*. It is accomplished by measuring the total quantity of water passing a given point in a stream, and from this determining the run-off from the watershed.

Units of measurement. — The two classes used represent quantity and rate of flow respectively. Units of quantity are the gallon, cubic foot, and acre foot. The first two may be employed to express the quantity of water stored or used for domestic purposes, but the last is more commonly used in engineering estimates of irrigation work. The *acre foot* is the amount of water required to cover 1 acre, 1 foot deep, and is equal to 43,560 cubic feet.

Fig. 155. — Hillside gullied by erosion, Lyell gullies, near Milledgeville, Ga. (T. L. Watson, photo.)

The rate of flow is the quantity of water flowing through a pipe or channel in a given unit of time, usually a second. The *miner's inch* and the *second foot* are the common units. A *miner's inch* represents the quantity of water which flows through an opening 1 inch square under a given head, usually 4 inches. A *second foot* can be defined as the delivery of 1 cubic foot per second of time. This is a more definite unit of measurement than the miner's inch.

The discharge is measured in second feet, and is determined by multiplying the cross-section of the stream, expressed in square feet by the average velocity in feet per second.

Second feet per square mile is the average number of cubic feet of water flowing per second from each square mile of area drained, it being assumed that the run-off is evenly distributed.

Run-off in inches is the depth to which the drainage area would be covered if all the water flowing from it in a given period were conserved and uniformly distributed over the surface.

Work Performed by Rivers and Its Engineering Application

The work performed by rivers is of three kinds, as follows:

1. *Work of erosion,* which is mainly of a mechanical nature, but in part is chemical. Through it the river carves its channel of variable size in either hard or soft rocks. The process is usually slow, except in soft materials, when under favorable conditions the process may be rapid and destructive.

2. *Transportation,* by means of which the stream removes more or less effectively the material derived from erosion, and the material supplied to it in other ways.

3. *Deposition,* or the dropping of the material which it has carried in variable quantity for different distances.

One problem of the engineer who has to deal with the work of running water is to see that the river performs these several functions at the proper time and in the proper place. The discussion of the latter will be kept separate so far as is possible, although this cannot always be done.

Work of Erosion

Introductory. — Erosion is the most expressive feature of stream work, for most streams carve their own valleys. The channel in the valley bottom which the stream is following is often larger than required by the volume of water flowing in it, but may be completely filled during periods of high water. Indeed during much of the year the channel is incompletely filled and the stream attempts to modify it in accordance with its needs.

The work of erosion performed by rivers may be mechanical (*corrasion*), and chemical (*corrosion*). Both may be going on at the same time, but the former is usually the more important of the two.

Corrasion. — The corrasive work of a stream is performed chiefly by the sediment which it carries. This consists of mineral matter ranging in size from fine clay to coarse stones depending on the velocity of the stream, the grains acting like cutting tools. A sluggish stream carries only fine sediment, while a mountain torrent carries or rolls along stones of large size (Fig. 156).

Water free from sediment has little erosive power, unless it is flowing swiftly over unconsolidated material like sand, or loose soil, but when running over hard rock, even though its velocity is high, the water alone has little wearing effect.

A heavy rainstorm falling on the soil of a hillside will sometimes carve a deep gully in a short time (Fig. 155), and neglect to prevent or stop this results in the removal of much material from the surface in some areas, and deterioration in land values. In all cases the damage is serious whether it involves the erosion of farm lands or railway embankments. Earth dams built of residual clay (*q.v.*) are also liable to injury from this cause.

FIG. 156. — Gravelly character of material carried by swiftly flowing stream. (T. L. Watson, photo.)

Keyes mentions the case of a shallow sloping trench which was built in a sandy western soil in order to protect a railroad grade from possible wash by sporadic rains. During a cloudburst this trench in one hour's time was enlarged to a gully 75 feet deep, 50 feet wide, and several miles long. The bulk of the dirt washed out was deposited at the foot of the sloping plain in a broad fan of more than a mile radius.[1]

In contrast to this we have the case of the swift, but sediment-free, Niagara River flowing over hard lichen-covered rocks, and yet not having enough corrasive power to remove the green vegetable growth.

Some corrasion is also done by ice along those streams where the

[1] Science, Feb. 22, 1918

banks are of loose material. This is accomplished either by the ice cakes rubbing along the banks as they float down stream, or when the ice is pulled away from the banks in spring and takes soil and stones with it.

Corrosion. — The work of solution or corrosion performed by a river is usually of secondary importance, except in limestone areas. All river waters contain dissolved mineral matter, but it is probable that most of this is contributed to the river by underground waters. Some mineral matter, however, is dissolved from the sides and bottom of the river channel, especially where the latter is of soluble rock like limestone, and the water is somewhat acid in character.

Factors governing rate of erosion. — The main factors affecting the erosive power of a river are slope, character and structure of rock, and climate.

The steeper the grade, the higher the velocity, and the greater the transporting power of the river; hence, other things being equal, the larger the amount of erosion it is capable of accomplishing.

Hard and firm rocks resist erosion more than loose and unconsolidated ones. Some years ago when the Colorado River broke through its banks and flowed down into the Imperial Valley (Fig. 157), the rapidity and depth of erosion accomplished by the New River flowing over sandy beds was astonishing. "Near the town of Imperial early in 1906, the river was flowing in a shallow depression, but by August a chasm had been cut there to a depth of 80 feet and with a width of 1200 feet" (Thomas and Watt).

But even very hard rock may be worn with comparative rapidity if it is traversed by a swift stream transporting resistant and sharp angular grains. Cases of this are frequently seen in sluiceways lined with vitrified brick or sheet iron, and used for carrying off sand, ore tailings, or granulated slag.

Stratified rocks, especially thinly-bedded ones, and much-jointed rocks, are more easily eroded than massive ones, and if the beds are tilted they succumb more readily than if they are horizontal.

In dealing with the improvement and regulation of navigable rivers the engineer is usually concerned with the erosion of soft rather than with hard material, and frequently has to guard against strong scouring action of streams during flood periods. One case illustrative of this, was that of a bridge constructed across the Saskatchewan River in Canada. Fifty-foot piles were driven into the sandy bottom of the river to serve as supports for the piers. Shortly after their completion the June floods scoured out the bottom to such an extent that the piles were carried away. They were replaced by eighty-foot piles,

the river bottom covered with matting, on which was dumped riprap, and then they remained.

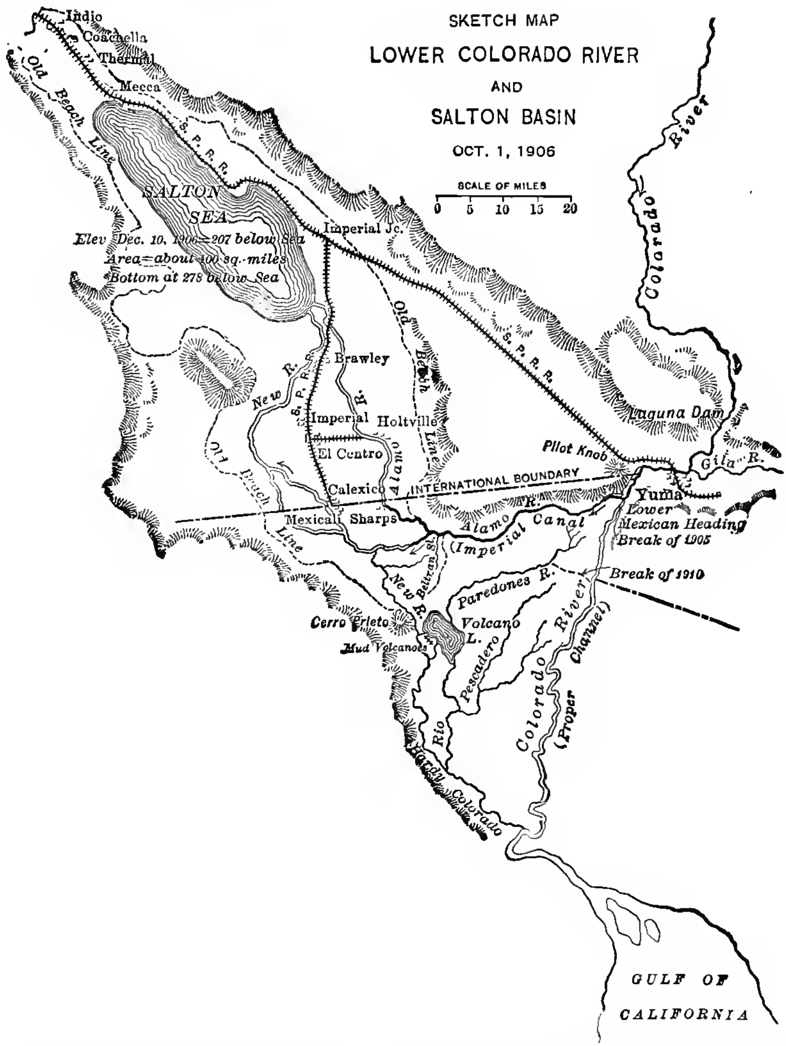

FIG. 157. — Map of Salton Sink and Imperial Valley, California. Shows points at which river broke through its banks. (From Thomas and Watt, Improvement of Rivers.)

Depth of erosion. — A stream at first cuts vertically or downward, and if no other natural agents, such as weathering, were coöperating with it, the valley would in the beginning have vertical walls, with the stream completely covering the bottom of the valley.

Cutting thus downward, a stream will tend to erode its valley until it reaches sea level, or the level of some other body of water into which it flows. This lowest level to which running water will usually wear a land surface is known as the *base level.* Some large rivers, like the Mississippi, carve their channels somewhat lower than sea level. A *temporary* base level is established in those streams emptying into inland bodies of water (lakes) which are elevated above sea level, or it may also develop where a stream is crossed by a very hard rock mass through which it can cut very slowly. From what has just been said, it must not be understood that the entire length of the stream reaches base level at the same time, since for a long period only the lower part of its grade may be cut down to this plane. On the contrary, the profile of a stream which has reached base level in the lower portion of its course, is that of a parabolic curve.

FIG. 158. — Patuxent River, Maryland. A river flowing nearly at base level. Note the sediment depositing on convex side of bends and supporting marsh growth. (H. Ries, photo.)

The head of the valley gradually works inland, and continues to grow by headward erosion until it reaches a point "where erosion towards the valley in question is equal to erosion in the opposite direction." (Chamberlin and Salisbury.) But while the stream is deepening its valley, the latter is also being widened at a variable rate by weathering and side wash. Particles of soil and rock are dislodged

from the valley sides by weathering agents, and carried down into the stream either by gravity or rain wash. Some of the material may be fine enough to be removed at once by the stream, but other portions may not be carried away until a flood comes.

After a stream has reached base level, it begins to cut laterally, thereby broadening its valley, in which it *meanders* or swings from side to side (Fig. 158).

Where several streams in adjoining valleys have cut down to base level, and begun to meander, the divides separating their valleys are gradually worn away. Thus the land surface is reduced to an almost featureless plain, at or near sea level, known as a *peneplain* (see further, p. 201).

FIG. 159. — Saskatchewan River, near Medicine Hat, Alberta. On concave side of curve, river has undermined cliffs, while on convex side, deposition has taken place. (H. Ries, photo.)

Character of meandering streams. — Meandering streams usually have a low velocity, and are easily deflected, so that if the bank is more easily eroded at one point than at another, it is sure to be cut into. If now the stream is directed against one point in the bank, it cuts in there, and the current, striking this bank obliquely, is deflected toward the opposite bank, and develops a curve there (Fig. 160). This action once started, continues, resulting in the concave bank being eroded more and more and the curves or meanders becoming continually more accentuated. The current will also be more rapid on the outer side of the curve.

This will naturally result in the dropping of sediment on the convex side, and crowding the current farther towards the concave shore (Fig. 159).

As the result of such shifting of the Mississippi River at Memphis, in a period of fifteen years, the left bank had increased its area 106 acres, with a maximum increase in width of 2300 feet, and parts of the former channel silted up 45 feet in one year. The change of the flow necessitated protection of the right bank for some distance.

The extreme curvatures of river channels thus developed are termed *ox-bows* (Fig. 160). When portions of adjoining curves almost touch, the river may become straightened either by artificial or by natural means, and a *cut-off* be formed (Fig. 160). The former consists in excavating a channel to connect neighboring parts of adjoining ox-bows, as in the case of Dutch Gap on James River, below Richmond, Va. The latter may be accomplished in two ways: (1) Either by the strip of land between two adjoining curves becoming so thin that the river breaks through, or (2) when the river covers most of the flood plain, by the main current during periods of flood, flowing across the neck of land (Fig. 160), thus cutting a new channel, which the river will then follow during normal periods. If the abandoned channel curve becomes separated from the main stream by sediment, and contains stagnant water it is called an *ox-bow* lake (Fig. 160). Such lakes are common along the middle and lower courses of the Mississippi River.

Shoals, bends, and crossings. — To the engineer the behavior of rivers flowing on an alluvial plain is a matter of some importance, especially if he is engaged in their regulation and improvement. From his viewpoint the river often consists of a series of bends, connected by straight reaches. The main current or volume of flow follows the concave shore, until a straight part of the channel is reached, when it crosses over gradually to the beginning of the next bend. This is known as a *crossing* (Fig. 160). Deep water is found along the concave bank, the deepest spot being usually below the point of sharpest curvature. On approaching the crossing, the flow spreads out, and as there is here a wider cross-section as well as an absence of eddies the sediment settles.

The wider the channel the greater the slackening, and the larger the amount of sediment deposited. Crossings therefore are found at low water to be shallow and of uncertain depths. In their widest parts the sediment may build up into bars or islands. Occasionally the straight reaches of a river, being narrow, keep free from sediment, as the volume of water scours them, so that they retain their same cross-section from year to year.

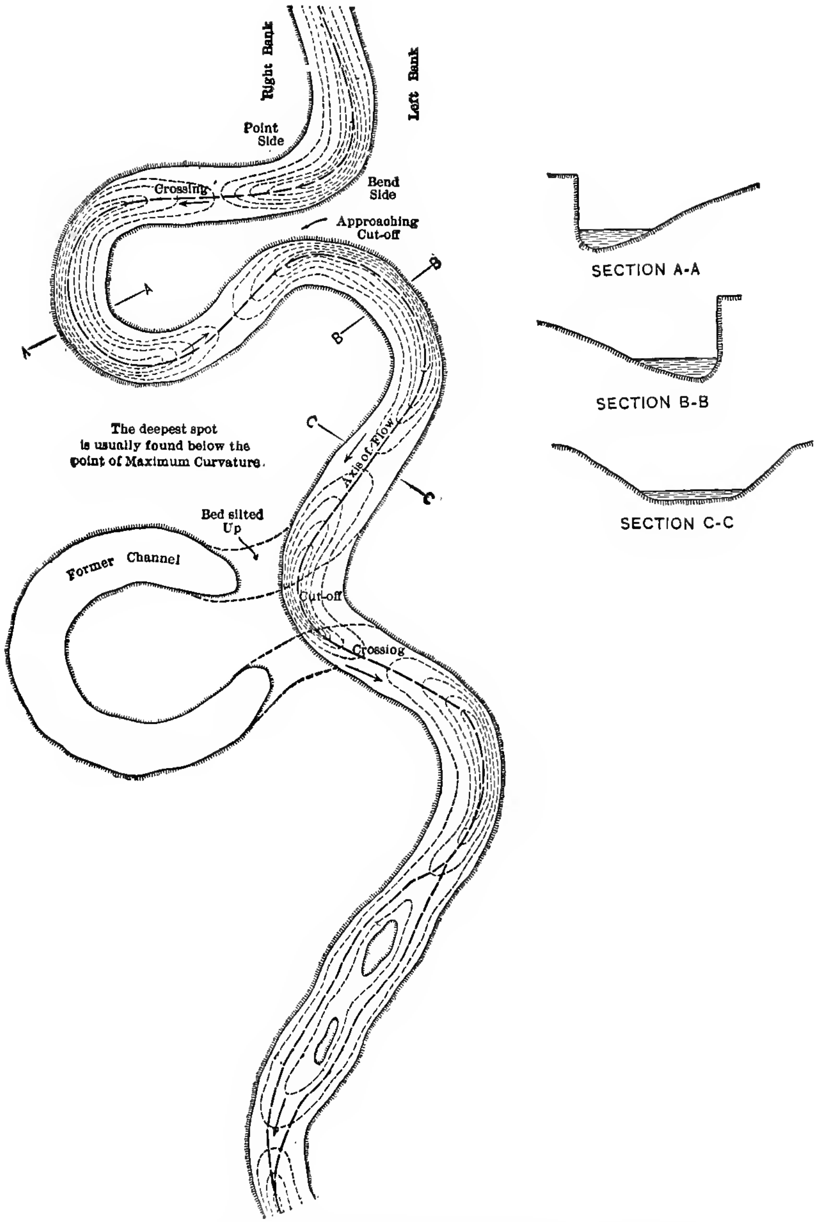

FIG. 160. — Plan and sections showing typical features of a meandering river. (After Thomas and Watt.)

Scour. — As has already been noted the scouring work performed by rivers is most noticeable in soft materials, where during a single flood the river may scour a deep channel. Such channels are, however, rarely permanent, and a slight deflection of the current may cause the previously scoured trench to fill up while another one is cut to one side of it. As a result of this the cross-section of the river channel at any given point in its course may vary greatly from year to year or even from flood to flood, unless means can be taken to control the stream current.

The effect of scour varies as the square of the velocity, and is dependent on the depth of flow. A river with a discharge 10 feet deep and 4 feet per second velocity, pressing on its bed with a weight of 625 pounds per square foot (10 feet of water at $62\frac{1}{2}$ pounds per foot), will have a much stronger scouring power than a brook of equal velocity only 1 foot deep, which would exert a pressure of only $62\frac{1}{2}$ pounds per square foot.

The material which the falling river has to remove is of varying compactness. If such material has settled it may have become so compacted as to resist the scouring action of the current, and even deflect it. The scouring process is a slow one, and if the river falls rapidly, the bar may become an obstruction to navigation, before there has been enough time to permit its removal by natural processes.

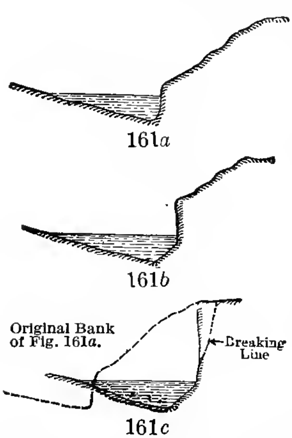

FIG. 161. — Sections showing successive stages of bank erosion. (*a*) Initial condition of bank; (*b*) erosion in progress; (*c*) bank cut back to vertical. (From Thomas and Watt, Improvement of Rivers.)

Erosion of banks. — Caving of river banks is due primarily to erosion. It may be caused by: (1) Water eating into the base of the bank; (2) the presence of an easily eroded layer of sand at the base of the bank, whose removal robs the latter of its support; and (3) the sudden fall of the river leaving a saturated bed unable to support the overlying load of the bank. Erosion is most active on the concave bank, or where there are eddies, and in either case goes on chiefly during periods of high water.

Figure 161*a–c* shows the successive stages of bank erosion. Figure 161*a* represents the initial condition of the bank. Figure 161*b* shows erosion in progress, with some caved material forming a temporary protection, which is soon washed away. In Fig. 161*c* the bank has been cut back to a

vertical surface, just before breaking. Needless to say saturation of the bank by rain water will hasten its collapse.

Protection against such erosion may be had by grading the bank to a flat slope, and covering its surface to high-water mark by non-erodable materials, or by breaking the attack of the water by spur revetments or spur dikes, or guarding the toe with a longitudinal dike of stone or piles. Railway embankments constructed along rapidly flowing streams are not infrequently undermined unless properly protected.

Levees. — When a river overtops its banks during periods of flood, and spreads over the flood plain, the sediment is deposited most actively on that part of the plain adjoining the river channel. As a result of this, low alluvial ridges or *natural levees* are built up, which may be a few or many feet in width.

In many regions the height of these natural levees has been increased by artificial means, high embankments being sometimes constructed to protect the alluvial plain from overflow during periods of flood. The most extensive example of levee work in the United States is that of the Mississippi and its tributaries below Cairo.[1]

Falls and rapids. — These are caused by irregularities in the hardness of the rock in the river channel, and form where streams pass from a more resistant to a less resistant rock (Figs. 162 and 163).

Thus, if we have a hard stratum outcropping in the bed of a stream, with softer beds below it, the greater wear of the latter develops sufficient inequality of bed to produce rapids. With progressing erosion and increasing steepness of the stream bed, the rapids change to *falls*. Continued erosion of the soft layer undermines the hard one and the falls migrate upstream, and although this movement is slow, plotted surveys extending over a series of years often show it clearly. If, however, the resistant rock is vertical (Fig. 162) and strikes across the stream, the falls may remain stationary until the hard layer is removed by erosion.

A waterfall may be formed in stratified rocks by the presence of hard beds interstratified with softer ones, or in other cases the development of the fall may be due to the existence of a hard dike or sill of igneous rock. Waterfalls may originate in other ways, such as inequalities produced by glacial erosion (see Hanging valleys, p. 307), but the above-mentioned causes are the commonest.

To the engineer the existence of falls and rapids is of importance, because the drop of the stream in a short distance permits its utiliza-

[1] For an excellent treatment of the subject of levee construction and maintenance see Thomas and Watt. Improvement of Rivers, 2d ed., pt. I, p. 243, 1913.

tion for power purposes, and hydro-electric plants are being constructed at many localities where such powers can be profitably developed.

Waterfalls and rapids, on the other hand, frequently interfere with navigation of a stream, and have to be passed in different ways. Falls can be passed sometimes by a series of locks, while rapids, if not too steep, can be overcome by blasting out the rock ledges in the stream bed, thus making a navigable channel. This was done for example on the Danube River in lower Hungary.[1]

FIG. 162. — Waterfalls over vertically dipping limestone beds. (Tomasopo Canyon, Mex.) (H. Ries, photo.)

Potholes. — In eddies and also at the foot of cascades or falls where the water has a swirling motion, the stones lying on the bottom are whirled around, and excavate cylindrical holes known as potholes, which are often well preserved in the solid rock. They vary in depth and diameter, some being of large size.

[1] See Thomas and Watt, Improvement of Rivers, I.

Work of Transportation

Transportation of sediment. — A river may transport mineral matter mechanically or in solution. The sediment moved mechanically by a river is either carried in suspension or rolled along the bottom, the latter being known as the *tractional load.* If the velocity of the stream decreases some of the suspended load settles and may be moved by traction or *vice versa.*

FIG. 163. — View looking east up Fall Creek gorge, Ithaca, N. Y. Falls flowing over horizontal strata.

The transporting power of a stream depends on its velocity, and is expressed by the equation

$$T \propto V^6,$$

in which T equals the transporting power and V, the velocity. If then the velocity is doubled, the transporting power is increased 64 times. But the velocity depends on grade, volume, and load. That is, the steeper the slope the greater the velocity; the greater the volume of flow for a given slope, the higher the velocity. Increased load tends to diminish the velocity. The last is shown by the fact that the velocity of a muddy stream is not as high as when the same stream is free from mud.

Amount of sediment transported. — The quantity of sediment transported by different rivers varies, owing partly to the variable quantity of débris supplied to different streams, and partly to their varying velocity. A swift stream flowing from a lake may even carry very little sediment, because the latter acts as a settling basin to separate the sediment from the water before it leaves it.

In the same stream the quantity of sediment carried will vary with the volume and velocity of the stream during different periods. Indeed, the quantity of sediment per cubic foot of water may not be the same in all parts of the stream's channel. Consequently, in making observations on the amount of sediment in a river, it is important to take samples of the water from different depths, and at different points of the section. In the Ohio River for example one ton of sediment passes Cincinnati every second. The following table is of interest in this connection.

PERCENTAGE OF MATERIAL CARRIED IN SUSPENSION BY VARIOUS RIVERS [1]

River.	Drainage area in square miles.	Mean annual discharge (in cubic feet) per second.	Total tons annually.	Ratio of sediment to water by weight.	Height in feet of column of sediment with a base of one square mile.	Thickness of sediment in inches if spread over drainage area.
Potomac	11,043	20,160	5,557,250	1 : 3,575	4.0	0.00433
Mississippi	1,244,000	610,000	406,250,000	1 1,500	241.4	0.00223
Rio Grande	30,000	1,700	3,830,000	1 : 291	2.8	0.00116
Uruguay	150,000	150,000	14,782,500	1 : 10,000	10.6	0.00085
Rhone	34,800	65,850	36,000,000	1 : 1,775	31.1	0.01075
Po	27,100	62,200	67,000,000	1 : 900	59.0	0.01139
Danube	320,300	315,200	108,000,000	1 : 2,880	93.2	0.00354
Nile	1,100,000	113,000	54,000,000	1 : 2,050	38.8	0.00042
Irrawaddy	125,000	475,000	291,430,000	1 : 1,610	209.0	0.02005
Mean	334,693	201,468	109,649,972	1 : 2,731	76.65	0.00614

[1] Babb, Science, XXI, p. 343, 1893.

Relation of size of particles to current velocity. — Experiments made to determine the relation between the size of particles transported and current velocity give rather uncertain results because of local conditions, such as the volume of discharge.

A river with a fall of one foot per mile can transport a large amount of heavy sediment, while a brook with similar fall can hardly carry silt. It has been noticed also, that while a current of given velocity may carry silt in suspension, a somewhat higher speed is required to erode the same material, and start it moving.

In irrigation canals leading from the Nile it was found that a velocity of 2 feet or less per second caused suspended silt to settle;

2.3 feet per second caused no deposit; while from 4 to 5 feet per second produced scour. A rate of $3\frac{1}{4}$ feet per second seemed to prevent both deposit and scour. According to Buckley, material in place will usually resist the following velocities per second: Sandy soil, from 1 to $2\frac{1}{2}$ feet; ordinary clay, 3 feet; compact clay, from 5 to 6 feet; gravel and pebbles, from 5 to 6 feet.

Relation of sediment to cross-section and slope. — The principles involved in the transportation of sediment by rivers make the chief law, which governs their behavior.

The burden of sediment may vary from mile to mile, but it usually remains in exact proportion of the water required to carry it, and this has been termed the *capacity* of the stream. A stream may therefore deposit at one point and scour at another; or acceleration of the current in a given stretch along its course may initiate scour, where previously deposition occurred.

"There should be in every part of a river a combined proportion between the discharge, the velocity, and the cross-section of the bed, or the amount of erosion affected by the stream" (Ref. 16). When a river rises in flood, therefore, it should deposit or scour the channel to the extent necessary to permit the passage of the water and its load of sediment. This exact condition is not always attained.

Measurements in low water show, however, that where considerable time has elapsed after a flood, the bends, where the water runs slowly in the low season, tend to silt up in proportion as the shoals, where the water runs fast, tend to erode. As a case in point, measurements taken on the Brazos River in Texas, over a distance of a few miles, comprising several bends and shoals, showed that the comparative areas of the bends and of the shoals sections did not differ by more than 10 per cent.

Slope of streams. — As already stated the valley slope determines the stream's velocity, and other things being equal the higher the velocity the greater the erosion. In general, a river has the steepest slope nearest its head, and least slope at its mouth, but aside from this there may be many local irregularities; and since a rise in the river causes increased velocity and slope, its bed and banks may change.

Tributaries exert an important local influence on a river's slope. If a tributary brings in much sediment, the main stream may receive more load than it can transport, and the sediment is deposited downstream, steepening the river bed in that direction, but reducing it above. "As a result deposits occur and the bed of the river is raised until equilibrium is again reached between velocity and sediment. A

sediment-free tributary adds to the volume of the main stream, and it begins to scour until it has its full load of sediment. This results in the slope becoming less than it is above the confluence of the two streams."

Work of Deposition

A river carrying sediment mechanically, begins to deposit the same when its current is checked. This deposition may occur: (1) In the river channel, (2) on the land bordering its course, and (3) at its mouth.

Channel deposits. — It has already been pointed out that a stream flowing in soft material may scour its channel at one time, and fill it up at another, the former often occurring during periods of flood and the latter during the normal water stage. Many streams, too, which in the upper parts of their course have considerable transporting power because of higher velocity, which in turn is caused by steeper slope, will on reaching the lower part of their course, slacken their speed, and therefore lose some of their transporting power and deposit some of their load. Because of this the channels of many streams are being silted up near their mouths.

The Sacramento River in California affords a most interesting case of a river channel becoming silted up by artificial causes. Here the débris from the placer mines in the hills was carried down to the main river, choking it up and causing floods. Subsequently with the cessation of hydraulic mining, and proper training of the river much of this débris has been moved farther down stream into San Francisco Bay. (Ref. 5.)

Alluvial plains. — Meandering streams which have cut down to base level do not occupy the entire width of their valleys and are bordered by flats of varying width. During periods of flood the river overflows the flats, and as the velocity of the stream is reduced over the overflowed flat it may deposit much of its load of sediment on such areas. The surface thus gradually built up or aggraded constitutes an *alluvial plain* or *flood plain* (Fig. 164).

With further development of the valley the flood plain extends farther up-stream, while at the same time its older parts may grow wider due to lateral erosion of the river. In some cases a flood plain may be formed by deposition alone, as when a stream becomes overloaded, while its valley is still narrow.

Flood plains may also be caused by either natural or artificial obstructions. A case of the former would be where a stream flows over resistant ledges, which act much like dams, checking the current

above them, and favoring the deposition of sediment. An artificial barrier or dam would produce similar results.

In some cases flood plains attain remarkable size, and extend upstream for great distances. The flood plain of the Mississippi has a width ranging from more than 20 miles at Helena, Ark., to about 80 miles near Greenville, Miss.[1]

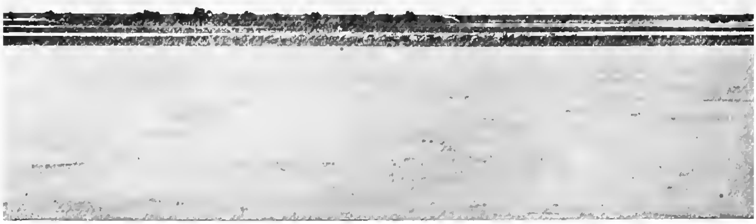

FIG. 164. — A flood plain. View along Danube River in Servia. (H. Ries, photo.)

Aggrading streams. — Rivers which build up their valley bottoms by deposition are said to be *aggrading.* The aggraded material is often built up unevenly, but may sometimes be very deep, the deposits in some old valleys being as much as 1000 feet thick. Some rivers like the Colorado are eroding in one part of their course, and aggrading in another. An aggrading stream may be generally recognized by its low slope, broad low bottom lands, meandering course, and river bluffs widely separated. Fords across such streams are likely to be soft, crossings difficult, and the bluffs sometimes of soft material not well suited for bridge piers.

Deltas. — When a sediment-laden stream enters a body of quiet water, its current is checked, and much of the material which it carries is dropped, but the finer material may be carried farther from the mouth of the river before it settles. Such deposits are termed *deltas,* and their extensive development at the mouths of some navigable rivers calls for considerable attention from the engineer engaged in river improvement, requiring the devising of satisfactory means for maintaining an open safe channelway across the delta to the sea.

[1] Mississippi River Commission, 1887.

The cause of this trouble will be better appreciated after the formation of the delta has been described.

The top of the delta deposit is comparatively flat, or to be more exact, the surface slopes gently away from the river's mouth so long as the river current is as deep as the standing water into which it is discharging, but beyond this the delta surface has a depositional slope. The result is the construction of a delta platform with a relatively flat top, and frontal slope of varying inclination.

As deposition continues, the delta platform is built up (aggraded), and at the same time its margin is extended seaward. The landward margin is gradually built up above sea level, and this land portion is also gradually extended outward.

In the beginning the main flow of the stream across the aggraded delta platform will be more or less in line with the main channel of the river above its mouth, but the current will shift somewhat to left and right, and yet since these shifting currents are of lower velocity than the main one, there will be a tendency for the sediment to build up on either side of the main channel forming natural levees. The main stream then finds itself flowing in a natural trench which it gradually extends seaward, but which at the same time is being filled up by further deposition. Its capacity to hold the flow of the main stream thus becomes reduced, and the latter finally breaks through the levee at some point, the greater portion of the flow following a new channel, which passes through the same changes as the first one. The main stream then, if left to itself will shift from one part of the delta surface to another.

The problem of the engineer is to maintain one of the channels across the delta to the sea in a navigable condition. One of the minor channels is usually selected for improvement because the advance of the delta at its mouth is slower, and hence the distance to sea shorter. Parallel jetties are built to prolong this channel out to the bar, so that the current, being concentrated across the latter, continues to scour. Fineness of sediment, deep water beyond the bar, and shore currents to carry off the sediment all contribute to the success of the operation. Bars may sooner or later form farther out and require prolongation of the jetty.

Structure of deltas. — In plan deltas are somewhat triangular resembling the Greek letter Δ.

In section the structure is as shown in Fig. 166. Here we see a series of inclined layers, the *fore-set* beds, which accumulated as the sediment rolled down the steep frontal slope of the delta. The finer material carried farther out constitutes the *bottom-set* beds, and these

are gradually covered by the fore-set layers as the delta is built seaward. At the same time material is being laid down in horizontal layers on top of the delta, forming the *top-set* beds.

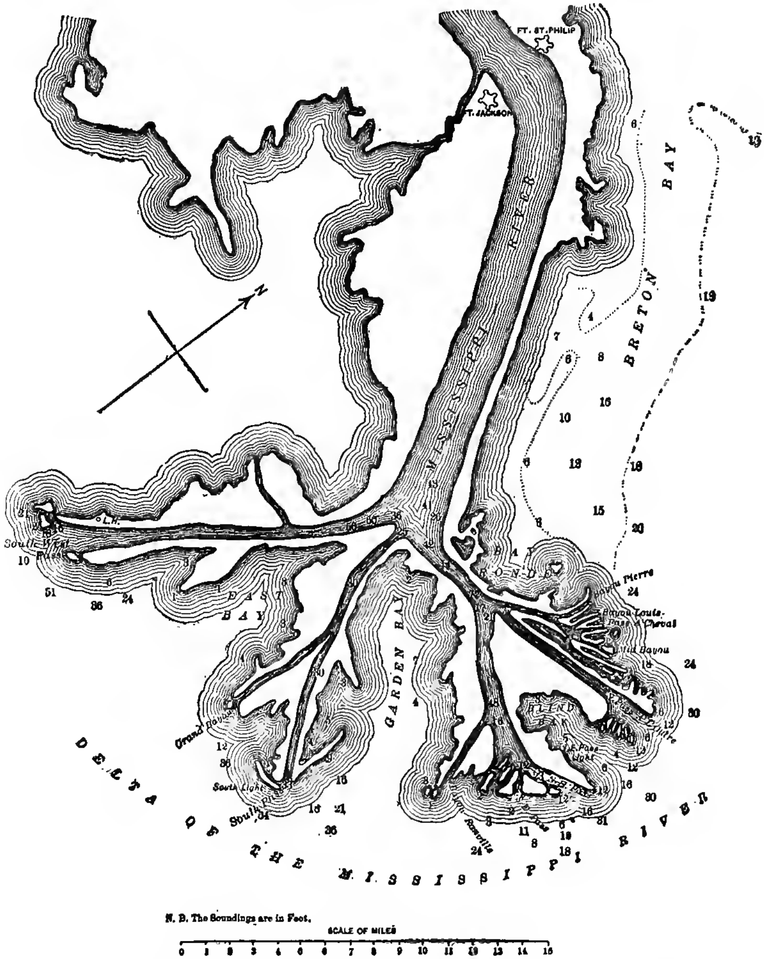

FIG. 165. — Plan of Mississippi delta. (From Thomas and Watt, Improvement of Rivers.)

Conditions favorable to delta formation. — All streams do not build deltas. Their absence may be due to: (1) lack of sediment; (2) waves and shore currents which carry off the sediment as soon as the streams deliver it; and (3) the great depth of water into which the stream discharges, which may take the sediment a long time to build up sufficiently to shallow the water.

The statement or theory that marine deltas are confined to tideless seas is incorrect, for a delta will form as long as the current of the sediment bearing river is stronger than currents in the sea which might tend to carry the débris away.

Lakes, bays, gulfs, and inland seas, where wave action and tidal currents are likely to be weak, are favorable for delta formation. Deltas are absent usually, or formed only at the heads of bays, along coasts that have been recently depressed, as in the Atlantic Coast region at present.

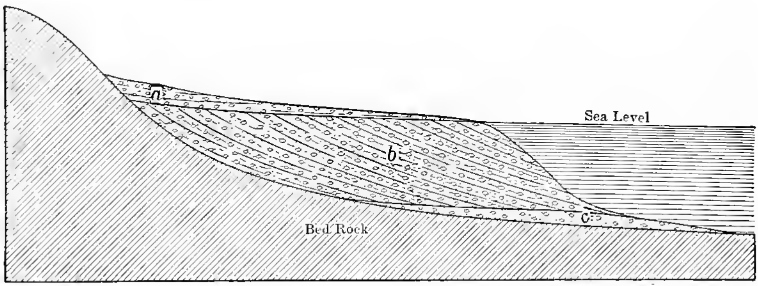

FIG. 166. — Section of delta showing: (*a*) top-set beds; (*b*) fore-set beds; (*c*) bottom-set beds.

Extent of deltas. — The deltas of large rivers are sometimes of vast extent, and are advancing seaward at a rapid rate.

The Mississippi delta, which has a length of over 200 miles and an area of over 12,000 square miles, is said to be advancing into the Gulf of Mexico at a rate of about 300 feet per year. Its depth at New Orleans is estimated at from 700 to 1000 feet.[1] The Yukon delta has a sea margin of 70 miles, and a length of 100 miles. The Hoang-Ho delta heads about 300 miles from the coast, and has a seaward border of about 400 miles.[2]

Some towns which were formerly sea-ports are now inland cities, because of delta growth. Thus Adria, formerly a port which gave its name to the Adriatic Sea, is now located 14 miles inland, because of the outgrowth of the Po delta. The latter is said to have advanced about 50 feet per year, but more lately the growth has been more rapid due to artificial embankments.[3]

Fossil deltas. — Subsequent to the formation of a delta, the waters of the lake or sea in which it originated may be drained off, either

[1] Humphrey and Abbott, Physics and Hydraulics of the Mississippi River; Corthell, National Geographic Magazine, VIII, p. 351, 1892.

[2] Dana, Manual of Geology, 4th ed., p. 198.

[3] Geikie, Textbook of Geology, 3rd. ed., p. 402.

due to the cutting down of the lake outlet, removal of the retaining dam (such as a glacier), or elevation of the land, as in the case of the sea or an estuary. These old deltas are often readily recognized by their flat tops, lobate fronts, and characteristic structure, and they aid in the interpretation of the geologic history of the area. (Fig. 167.)

Along the Hudson River valley in New York state many splendid fossil deltas (Fig. 167) are found. Others are seen along the old shore lines of the Great Lakes in the north central states, etc.

FIG. 167. — Section of ancient delta, Fishkill, N. Y. (H. Ries, photo.)

The fossil deltas often serve as important sources of sand or gravel for structural work, filter beds, etc. In railroad construction they are sometimes drawn upon for material to make fills across valleys. The flat tops of the old deltas often serve as splendid sites for towns, shops or factories.

River terraces. — Many streams are bordered by natural benches or terraces (Fig. 167), which are usually somewhat narrow, but may often have considerable length parallel with the river. One or several of these terraces are often present, and form benches on one side of the stream valley, or there may be corresponding ones at the same level on the opposite side, although this is not always the case. In some cases these terraces are so level and well developed as to make the layman suspicious of their origin by natural processes. Terraces are of two kinds, *flood plain* terraces and *rock* terraces.

Flood plain or alluvial terraces. — These originate as flood plains underlain by alluvium. For a time the river may cover this flood plain during high water, but as it cuts deeper the plain is no longer inundated and remains bordering the stream as a terrace. If the river level remains stationary for a time its meanders may cut into the embankment of the terrace and a new flood plain be developed. If this is abandoned by renewed down-cutting of the stream a second level terrace results.

A slightly different type of alluvial terrace is that found along the Hudson River valley in New York state. Here the old gorge, formed when the land stood at a higher level, was subsequently submerged by depression of the continental margin. During this latter period the gorge was filled in part by a thick deposit of clay. Subsequently when the land was reëlevated the river cut its channel in the clay leaving much of it, however, in terraces on both sides of the river.

The material underlying alluvial terraces is often drawn upon for a variety of purposes, depending on its character, such as gravel, building sand, or clay for bricks. The terrace material is at times also sufficiently permeable but retentive to hold groundwater for shallow wells.

Rock terraces. — These are formed by a river meandering over a rocky valley floor, and subsequently renewing its downward erosion, thus leaving the rock plain above water level as a terrace.

Outlets of rivers. — The outlets of rivers are of three general types:[1] (1) Those which discharge directly or indirectly into seas where the range of tide and the violence of the storms are limited, such as the Danube, the Nile, the Mississippi, certain rivers flowing into the Baltic, etc.; (2) those which discharge through estuaries, such as the Thames, the Seine, and the St. Lawrence; and (3) those which discharge directly into oceans and are exposed to all the changes produced by sand drift, tidal effects, etc., such as most of the rivers of the Atlantic and Pacific coasts of the United States. Of these three types the third is perhaps the most difficult to improve.

Bars at mouths of rivers. — Bars, sometimes constituting a trouble or even a menace to navigation, are found at the mouths of nearly all rivers. They may be formed in several ways:

1. In the case of sediment-bearing rivers like the Mississippi, Nile, Amazon, etc., or rivers entering lakes or inland seas, checking of the current on entering still water causes it to drop its load resulting in the formation of a bar.

2. Where a river enters a lagoon or bay of a tidal sea, the bar may be formed by wind and waves driving sediment across the mouth (see Bars, under Ocean Waves and Currents, Chapter VII), and the river channel is kept open by tidal currents.

[1] Thomas and Watt, I, p. 309, 1913

3. The formation of a bar across the mouth of a tidal estuary may be due to eddies and still water produced by ebb and flood currents at the entrance, or to littoral or shore currents which drift material across the mouth of the estuary.

Drainage Forms and Modifications

Development of valleys and tributaries. — A valley usually has its beginning in a gully formed by rain-wash. This serves as a line of concentration for more surface water during successive storms, and so becomes enlarged, being washed out deeper each time. At the same time it may be lengthened by headward growth (erosion) and widened by rain-wash from the sides. Irregularities of slope are likely to produce sinuosities in the stream, which are the beginnings retained by the valley when it has developed more. Since the water flowing down the slopes of a gully follows lines of depression, so branch gullies originate from similar inequalities of slope or hardness of rocks, and these tributaries develop in the same manner as the main stream. Tributaries as a rule join their main stream with the acute angle up-stream.

Although a valley may extend up-stream, that is headward, it will continue until it reaches a point where erosion from the opposite direction counterbalances it. If, however, erosion on opposite sides of a divide is unequal, the latter will slowly move towards the side of less rapid erosion.

If on a new land surface we have a series of somewhat parallel gullies developed, these will tend to concentrate the drainage. A gully widens by water entering from the sides, and lengthens by wash at its upper end. Every gully, however, does not develop into a stream valley, for if one deepens and widens more rapidly than a neighboring one, the latter may become absorbed or eliminated by the destruction of the ridge between them. Moreover, those gullies which develop headward more rapidly will send out tributaries, and cut off the up-slope supply of those which did not work headward as fast.

If a series of somewhat parallel valleys develop on a new land surface they will occupy a series of trenches, separated by elevations as yet not much dissected by erosion, although a few tributaries may have developed. As the stronger streams deepen and widen their valleys these inter-stream areas become narrower. At the same time the tributaries increase in number and intersect the inter-stream areas, cutting them into a series of cross ridges. By a continuation of this process the ridges separating the valleys become obliterated by erosion and weathering, resulting in reducing the land surface to a nearly common level and in the development of a *peneplain*.

If a drainage system develops on a series of rocks of unequal hardness, the hardest rocks will resist erosion most, so that they remain as ridges even after the soft rocks have been leveled down.

If a stream crosses a tilted bed of hard rock lying between softer ones, the valley will widen more both above and below the hard bed than it does where the stream crosses it. If the hard beds are vertical, so that their outcrop does not shift as erosion proceeds, a *narrows* is developed.

The formation of gullies may begin without much regard to the degree of hardness of the rocks, but with further development the relation of streams to rock structure often becomes emphasized. Thus a stream flowing over a soft, less resistant rock, deepens its valley more rapidly than one flowing over hard rock. More rapid erosion also takes place when a stream flows across rocks of unequal hardness, than over rocks which are all hard.

As time goes on the streams show a tendency to follow the softer formations, so that the harder ones become divides, and there is thus an adjustment of the streams to the underlying rock structure. Joint planes, because they are lines of weakness, may also exert a guiding influence on stream drainage.

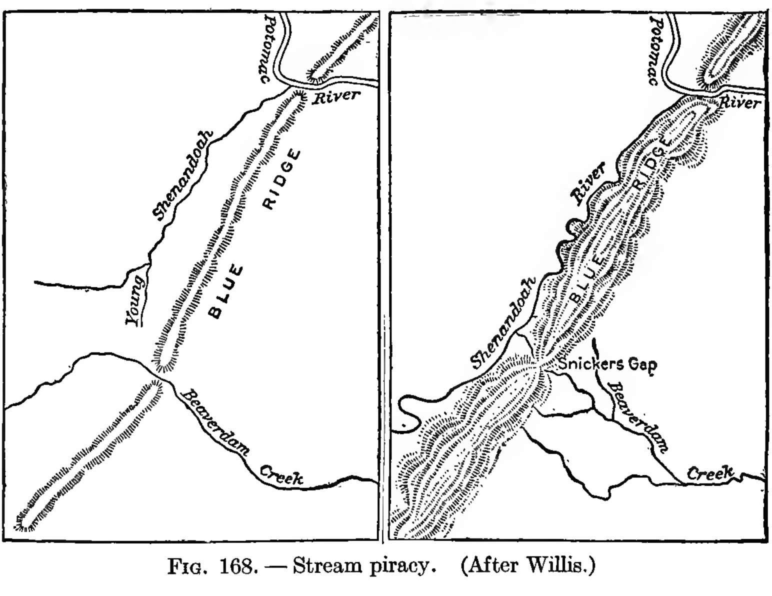

FIG. 168. — Stream piracy. (After Willis.)

Piracy. — Neighboring streams do not always develop with equal rapidity, because of unequal conditions, such as difference in slope, character of rock, size of streams, etc. One stream gains the advantage over the other by more rapid develop-

ment through headward erosion, so that the more able-bodied stream constantly pushes the divide into the territory of its weaker neighbor, and its headwaters finally cut into the upper reaches of the other. Thus the head of the second stream or of one of its tributaries becomes diverted into the channel of the first. This is known as *piracy*.

As shown in Fig. 168, Beaverdam Creek once flowed across the Blue Ridge, which at Snickers Gap is of hard rock. The stream was unable to deepen its bed across the hard rock of the ridge as rapidly as the larger Potomac lowered its channel across similar rock. The result was that the head of a tributary of the Potomac worked back and tapped Beaverdam Creek. By this process the *water gap* (at Snickers Gap) became a *wind gap*.

FIG. 169. — View looking west down Fall Creek gorge, Ithaca, N. Y. A post-Glacial gorge cut in shales. In the distance is seen the valley at the head of Cayuga Lake; a mature valley with gently sloping sides, and filled in by drift and delta deposits to a depth of over 400 feet.

Young and old topography. — Narrow and steep-sided valleys cut in a land area of a humid region are said to be *young*, and the territory traversed by them is in its *topographic youth*. Young streams are usually swift, they cut vertically rather than horizontally, and their grade is often interrupted by rapids and falls. At this stage the stream has acquired but few tributaries. Valleys approaching base level develop flats. As these flats widen, and the tributaries increase in number and size, the valley slopes become gentle, and the topog-

raphy is said to be *mature.* In Fig. 169, we see a young valley tributary to a mature one.

Old streams usually have a low grade, and a sluggish current. They erode during floods, and deposit their load and fill their channels at other times. Meandering is a characteristic feature of old streams, as illustrated in the Mississippi.

Formation of canyons. — A high altitude is favorable to the development of swiftly-flowing streams and deep valleys, and if the conditions promoting widening are absent, the valley will be narrow. In arid climates the conditions are usually favorable to the development

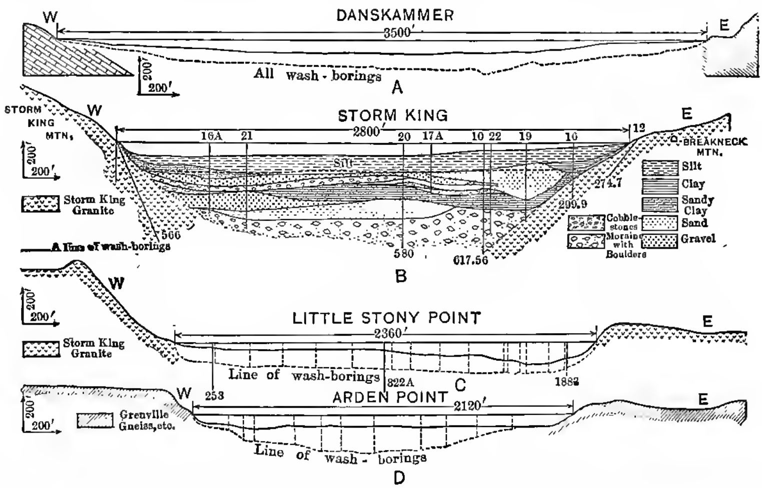

FIG. 170. — Sections across the Hudson River Valley. *A*, the Danskammer crossing; *B*, the Storm King crossing; *C*, the Little Stony Point crossing; *D*, Arden Point crossing. (After Kemp, Amer. Jour. Science.)

of deep narrow valleys or *canyons.* Firm rock is also a condition favoring their growth. The Colorado canyon is one of the finest examples of its kind known. A small canyon is usually termed a *gorge* (Fig. 163), such as that part of Niagara River from the falls northward.

Buried channels. — The drainage systems of a region are sometimes seriously disturbed by different natural processes as follows: (1) Lava flows may obliterate the river valleys of an area and necessitate the establishment of new ones; indeed cases of this sort are not uncommon in the far west. (2) River drainage may be displaced by glacial action. Prior to the advance of the continental ice sheet in recent geologic times, there were well-established drainage systems. In many cases the pre-Glacial river valleys were completely filled

with glacial drift, so that after the ice withdrew these rivers had to cut new valleys. In some cases these new (post-Glacial) valleys were cut in the drift filling of the old or pre-Glacial valley (Fig. 193), in others the river has cut a gorge in the rock at one side of the buried channel (Fig. 169), and in still other cases a part of the present valley is excavated in the glacial filling and a part in the solid rock.

FIG. 171. — View of Hudson River valley, looking north from West Point, N. Y. The river here flows through a deep gorge that has been depressed below sea level, and partly filled by sediment and glacial drift. (H. Ries, photo.)

These buried channels are not always known to the engineer, and when encountered, as they sometimes are, in tunneling operations, they may be a source of both surprise and trouble. Because of the wide area covered by glacial deposits this type of buried valley is of considerable interest to the engineer. The material filling the old valley is sometimes sufficiently porous to serve as a reservoir for underground water. Several buried channels were encountered in the construction of the Catskill aqueduct for New York City, and are referred to in Chapter X.

(3) A river may cut a more or less deep valley in bed rock and then subsequently fill it with sediment, often of a sandy or gravelly character. In some instances these deposits are several hundred or a thousand feet in thickness.[1] Like the glacial filling they too may be water bearing.

[1] See Lee, W. T., U. S. Geol. Surv., Bull. 352, 1908.

(4) River valleys which enter the ocean sometimes become filled by the land being depressed so that the valley is flooded by sea water and becomes an estuary in which fine sediment settles.

The Hudson River valley is a fine illustration of this. In recent geologic times the land of the Atlantic coast stood much higher, so that the Hudson River carved a deep gorge, whose continuation can be traced by a trench on the sea bottom some distance beyond New York bay. Similar valleys carved in the submerged continental shelf bordering the Atlantic Coastal Plain have been traced opposite the present mouths of several of the pre-Glacial streams of the eastern United States. Subsequently the land was depressed lower than it is now and the Hudson River gorge was filled by clay and sand brought down by the river, and in part by glacial drift (Fig. 170). This was followed by a slight reëlevation, bringing the estuary clays about 200 feet above present sea level in the Highlands. When it became necessary recently to carry the new aqueduct under the Hudson (Fig. 171) by means of an inverted siphon, the engineers found it necessary to go nearly 1000 feet below the river level in order to cross in the rock bottom.

Floods and Dam Foundations

Floods and their regulation. — A river which is irregular in its discharge may cause trouble: First, by having a deficiency of water for navigation, power or other purposes in dry weather, and second, by discharging an excess during another period, the volume being dangerous to navigation and injurious to property.

When therefore the quantity of water supplied to the river is of greater volume than the channel can accommodate, the water overflows the banks and floods adjacent territory.

The causes producing floods are: (1) Excessive rainfall; (2) rapid melting of accumulated snow; (3) steep slopes which permit the water to drain off rapidly into the rivers; (4) absence of vegetation which can retard the run-off; (5) impervious soil; (6) failure of reservoirs; (7) formation and failure of ice jams; and (8) breaking of levees.

These may act jointly or singly, and the great problem is the prevention of flood damage, especially by the first two of the above causes.

Any method for flood prevention must be based on retardation of the run-off.

Lake basins serve as natural reservoirs to hold water and prevent its being delivered too rapidly to the rivers. The best example of

natural reservoirs known in the world is the chain of Great Lakes, which exercises a complete control over the St. Lawrence River.[1]

An artificial application of the above principle lies in the construction of reservoirs on the tributaries of a large stream. During flood periods these fill up, and during low water stage of the river, the water from the artificial lakes can be let out to maintain a proper level in the stream.

Unfortunately the cost of such a project in the case of a large river like the Allegheny and Monongahela or the Ohio is so great as to be almost impracticable.[2]

Other methods of flood prevention would include: (1) Preservation of forests and grass on slopes of drainage basins; (2) drainage of lands to keep the soil dry, so that during rainy periods it will absorb more water; and (3) contour plowing to retard the run-off.

Floods may also be controlled to some degree by: (1) Construction of levees, (2) straightening of channels to increase the stream discharge, and (3) deepening the river channel.

Ice gorges. — The ice in some streams, when it breaks up, becomes piled against an obstruction such as a shoal or bar and forms a temporary dam. Such a dam may obstruct the stream flow to a considerable extent, so that when the pressure of the water behind the dam causes it to burst, a serious flood may result. In some cases the ice dam bursts and naturally passes down-stream, only to become lodged again at another point below.[3]

It seems difficult to prevent floods due to ice gorges on streams, and it is sometimes almost impossible to keep an open channel in winter. Explosives are occasionally used, but the stream often becomes blocked for many miles. About the only remedy to be applied is to remove, as far as possible, the causes preventing the movement of ice.

Dam foundations. — Since dams are constructed for the purpose of storing river waters, it is not out of place here to discuss briefly the relation of geologic structure to dam foundations, even though the subject is also referred to in Chapters VI and X.

In dam construction it is essential that the foundations should be sufficiently strong to bear the weight of the dam and also sufficiently tight to prevent seepage under or around the structure.

[1] For an excellent discussion on this subject see Reservoir Sites in Wyoming and Colorado, by H. S. Chittenden, House Doc. 141, 55th Congress, 2nd Session, 1898.

[2] See Reference 7, also U. S. Geol. Survey, Wat. Sup. Pap. 334, 1913.

[3] See for example case of Susquehanna River Flood, Pa., U. S. Geol. Survey Wat. Sup. Paper 147, p. 25, 1904.

The character of the foundation may determine the height of dam which it is practicable to construct, and the amount of storage capacity which may be made available. Many dam failures are due to neglect to thoroughly investigate the character of the foundations, for soundings and borings should be carefully made before finally locating any dams or locks.

Care should be taken not to mistake boulders for bed rock. The need of these precautions is not only to insure the safety of the dam, but also to save expense, for it is often very costly to patch up defective foundations after the work is once started.

Bed-rock foundations. — In some cases the bed rock outcrops at the surface, or has but slight covering over it on the stream bottom, but in any event care should be taken to ascertain its tightness and continuity.

Limestones are apt to have solution channels, which would permit underflow, and these should be filled up, or else, if of shallow nature, the bed rock should be removed until it is solid. The Hale's Bar dam on the Tennessee River is a conspicuous case of trouble caused by solution cavities in limestone, and much time and expense were caused in getting these water-tight.

Sandstones may have interbedded shale layers, which become softened by water percolating along them and causing the foundation rock to slip, unless the trench for the dam is carried sufficiently deep.

Fig. 172. — Basalt flow overlying stream gravels, central France. (H. Ries, photo.)

Some stratified rocks are so seamed by joint planes, especially near the surface, as to give cause for concern on account of danger from seepage. Among the igneous rocks, the porous volcanics, and especially tuffs and agglomerates, are sometimes liable to be very porous and need grouting (see p. 36).

It must not be assumed from what has been said above that the

types of rock mentioned always cause trouble, but these cases are cited simply to show the need of precaution.

Where solid rock is struck, it should be bored to a sufficient depth to prove that it is not a thin layer, such as a lava flow resting on other material (Fig. 172), or an overhanging ledge of a buried stream channel. Moreover, it must not be assumed that because bed rock is found at a given level on one side of a river, that it will be found at a similar level on the other side.

Valleys are sometimes cut along the contact of two formations, which, as explained on page 143, may be a line of weakness and solubility.

Unconsolidated material. — This may consist of gravel, sand, or clay, either alone, or interbedded, or intermixed. These materials if found in the valleys may represent river deposits, lake deposits, or glacial deposits. If the last, the material might be either modified drift (Chapter X) consisting of indifferently bedded sand or gravel, or it may be till (Chapter X), a heterogeneous mixture of boulders, clay, and sand.

Unconsolidated materials should be carefully tested for dam foundation work, for although they may consist of dense, water-tight material on top, there may be permeable beds or lenses below.

Gravel foundations usually permit seepage. With sand, or clay and sand mixed, there is danger of seepage or undermining from above, and danger of erosion on the down-stream side of the dam. Sheet piling is commonly used to protect it on the up-stream side. Coarse and fine sand mixed seem to have a greater bearing power than sand and clay. Clay is not a very common foundation for structures in rivers, but when present may vary from the compacted silt of abandoned river channels to the hard clay which will stand a strong current almost unaffected. This last variety of clay is rare in river work, but is excellent for foundations, as it is water-tight and usually of high bearing power. With the softer variety of clay it is not safe to trust much to the bearing power of the material unless it has been shown by tests to be reliable in this respect. Even when confined by sheet piling (as should always be done on those sides of the structure where there is any possibility of the material spreading under concentrated load), such clay is liable to flow gradually, and displace the masonry resting on it.

Composition of River Water

River water may contain various mineral substances: (1) Suspended matter, which may consist of silica, iron oxide or alumina, in part

colloidal; (2) dissolved gases such as carbon dioxide; and (3) various dissolved solids. These expressed in ionic form include aluminum, iron, calcium, magnesium, sodium, potassium, hydrogen, carbonate radical (CO_3), bicarbonate radical (HCO_3), sulphate radical (SO_4), nitrate radical (NO_3), and chloride radical (Cl).

The dissolved mineral matter may be derived from: (1) Spring water, which is the chief source; (2) solvent action of the river water on its banks, or sediment it carries; (3) rain wash; and (4) artificial sources as factories, sewers, etc. The last may cause considerable contamination by discharging both mineral and organic substances into the river.

The composition of a river water is of importance for several reasons as follows:

1. Drinking water should be hygienically pure and free from contamination, hence the watersheds of streams supplying it are carefully watched. In England and the eastern United States, 570 parts per million has been fixed by some authorities as the permissible limit of mineral content in drinking water, but in desert regions waters containing as much as 2500 parts of total dissolved solids have been used for drinking. From 250 to 300 parts of chlorine derived from common salt gives a slightly salty taste, but some water with as much as 600 parts is often used without injury. About 400 parts of the sulphate radical in form of Glauber salt gives a perceptible taste.

2. Boiler water should be free from substances present in sufficient quantity to cause scale, foaming, etc. Railroads have to give careful attention to water for engines used along their route. The formation of scale is due to the *hardness* of the water, or its capacity to form insoluble compounds due to a reaction between soap and certain dissolved substances in the water such as calcium, magnesium, iron, and aluminum. The calcium and magnesium are usually present as sulphates and bicarbonates, but their chlorides may also cause hardness.

The hardness is *temporary* if it can be removed by heating and treatment with lime; and *permanent* if it can be removed only by treatment with soda or other alkali.

Foaming in boilers is caused by sodium and potassium carbonates when present in considerable quantity. Corrosion may be caused by water containing free acid, as it does in some coal mining districts where the decomposing pyrite in the coal yields sulphuric acid to the spring waters. Thus the Monongahela River water in places is so acid as to be unfit for use in boilers, and it is said that three-eighths inch plates at the canal locks have been eaten to a knife edge in one year's time.

3. Irrigation water should not contain any considerable quantity of soluble salts, as they are injurious to growing crops. The total quantity of soluble salts or alkali permissible depends on the character of salts, the natural condition of the soil, amount of irrigating water used, and efficiency of underground drainage. Waters of arid regions contain a larger quantity of dissolved salts than those of humid areas.

4. Bridge piers or other submerged masonry, if constructed of porous rock, have sometimes been damaged in the West where exposed to waters with a high percentage of soluble salts. At high water, the river water was absorbed by the stone, then when the rocks dried out as the river fell, the soluble salts crystallized out in the pores of the stone. Repetitions of this have sometimes caused disintegration of the stone.

Statement of water analyses.[1] — The composition of a river water may be expressed in several different ways as below.

ANALYSIS OF WATER STATED IN DIFFERENT FORMS

	Grains per imperial gallon.		Parts per million.		Per cent
SiO_2	0.891	$CaSO_4$	457.7	SiO_2	1.26
SO_3	82.601	$MgSO_4$	236.0	SO_4	55.28
CO_2	4.554	K_2SO_4	9.4	CO_3	8.78
Cl	2.681	Na_2SO_4	62.5	Cl	3.79
Na_2O	11.643	NaCl	63.2	Na	12.02
K_2O	0.355	Na_2CO_3	156.9	K	0.41
CaO	13.117	Na_2SiO_3	21.9	Ca	13.24
MgO	5.530	$(FeAl)_2O_3$	2.7	Mg	4.69
$(FeAl)_2O_3$	0.189	Mn_2O_3	2.7	R_2O_3	0.53
Mn_2O_3	0.189	Ignition	34.2		100.00
Ignition	2.397	Excess SiO_2	1.3		
	73.967		1048.5	" Ignition " omitted	
Less O = Cl	0.604			Salinity, 1014 parts per million	
	73.363				

In the first column the results are given in terms of oxides, etc., as in a mineral analysis, and in grains to the imperial gallon. In the second column they are stated in terms of salts, and expressed in parts per million. In the third the composition of the anhydrous residue left on evaporating the water to dryness is given, expressed in radicals or ions, and in percentages of total anhydrous inorganic solids. Under salinity is given the concentration of the water in terms of parts per million. One million parts of this water contain in solution 1014 parts of anhydrous, inorganic, solid matter.

[1] See F. W. Clarke, U. S. Geol. Surv., Bull. 695, p. 60, 1920.

Relation of river water to rock formation. — The amount of dissolved mineral matter in the natural surface waters depends mainly on the nature of the rock formations traversed, on climatic conditions, and on amount of vegetation.

Two streams flowing over different kinds of rocks may show a difference in composition; or again a stream flowing over a limestone formation, and receiving tributaries from a schist area, will show a difference in composition in different parts of its course (Ref. 12).

The Cache la Poudre River in Colorado affords a most interesting example of such changes.[1] Another case is that at Oneida, N. Y., the water supply of which has been obtained from a river flowing over Salina shales which are gypsiferous. On account of the high $CaSO_4$ content and hardness, the water is to be abandoned, and a new supply obtained from a river flowing over sandstone yielding excellent water.[2]

When one considers the number of different rock types over which rivers flow, and the difference in weathering processes between humid and arid regions, it is not surprising that the rivers of the United States show a wide range in composition. (See Ref. 3 for many analyses.)

References on Rivers

1. Chamberlin and Salisbury, Geology, 2 ed., Vol. I, p. 54, 1905. (Holt and Co.) 2. Chittenden, Amer. Soc. Civ. Engrs., Trans., 1908, and Eng. News, Oct., 1908. (Relation of forests to stream flow.) 3. Clarke, U. S. Geol. Survey, Bull. 695, pp. 65, 88, 1920. (Many analyses.) 4. Glenn, U. S. Geol. Survey, Prof. Pap. 72, 1911. (Denudation and erosion in Southern Appalachians.) 5. Gilbert, U. S. Geol. Surv., Prof. Pap. 105, 1917. (Sacramento River.) 6. Gilbert, U. S. Geol. Surv., Prof. Pap. 86, 1914. (Transportation of débris by running water.) 7. Heinz and others, Report of Flood Commission of Pittsburgh, Pa., 1912. (Contains excellent bibliography.) 8. Jackson, U. S. Geol. Survey, Water Sup. Pap. 144, 1905. (Normal chlorine in N. Y. and New Eng. rivers.) 9. Leighton, U. S. Geol. Survey, Wat. Sup. Pap. 79, 1903. (Relation between normal and polluted waters, eastern U. S.) 10. McGee, U. S. Dept. Agric., Bur. Soils, Bull. 71, 1911. (Soil erosion.) 11. Newell and Murphy, Principles of Irrigation Engineering, 1913, New York. (McGraw-Hill Pub. Co.) 12. Palmer, U. S. Geol. Survey, Bull. 479, 1911. (Geochemical interpretation of water analyses.) 13. Rafter, U. S. Geol. Survey, Wat. Sup. Pap. 80, 1903. (Relation of rainfall to run-off.) 14. Russell, Rivers of North America, 1898, New York. (G. P. Putnam's Sons.) 15. Stabler, Eng. News, LX, p. 356, 1908. (Interpretation of mineral analysis of water.) 16. Thomas and Watt, Improvement of Rivers, 2 vols., 2nd ed., 1913, New York. (Wiley & Sons, Inc.) 17. Meinzer, Military Geology, Chap. III, 1918. (Yale Univ. Press.)

See also numerous Water Supply and Irrigation Papers published by the United States Geological Survey. Many of these relate to stream gaging.

[1] Headden, Bull. Colo. Agric. Exper. Sta., No. 82, 1903, p. 56.

[2] Chem. News, vol. 115, p. 109, 1917.

CHAPTER VI

UNDERGROUND WATER

Introduction. — It is a well-known fact that the rocks of the earth's crust, as determined by borings and mining operations, contain more or less water. The occurrence, distribution, and movement of this water are of interest to the engineer for several reasons: (1) Underground water often serves as a source of water supply, and (2) it frequently affects engineering operations, such as tunneling, dam foundations, stability of embankments, etc.

Sources of underground water. — The water found in the rocks may be of three different kinds, viz., *magmatic*, *connate*, and *meteoric*. The first and third sometimes reach the surface as springs, but only the third (meteoric) is of great importance as a source of underground water supply, and, therefore, the other two can be briefly disposed of first.

Magmatic or *juvenile water* is that which is given off by magmas during the process of cooling and consolidation (Chapter II). It comes from unknown, variable depths, and is important because it has played an active rôle as a transporting and depositing agent of ore minerals. Such water is occasionally encountered in mine and tunnel workings, and may reach the surface as hot springs. It is not to be regarded as a source of underground water supply, but sometimes on account of its high mineral content is of medicinal value.

Connate water is water which is indigenous to the rocks containing it, such as original sea water in a sedimentary rock or magmatic water in an igneous rock. It is occasionally tapped by bored wells which penetrate sedimentary rocks.

Meteoric water represents that part of the rain water including melting snow which has soaked into the rocks. It is vastly more important than the other two kinds.

Absorption. — As has been pointed out on p. 174 some of the rain or snow which falls on the surface may soak into the ground, and the quantity so absorbed is controlled by a number of factors. This absorbed portion (the *run-in*), some of which may soak into the ground from river channels, ranges from less than 1 per cent up to even 95 per cent.

It is said (Ref. 6) that "fairly definite estimates of the amount of water absorbed by the ground can be made by measuring the loss of water from certain streams in arid regions that flow above the water table for considerable distances and for periods of considerable duration but in most regions only indirect methods that give somewhat uncertain results are available."

Groundwater. — Some of the water absorbed by the ground (Ref. 7) is held in the pores of the soil near the surface, but most of it moves downward into the deeper layers of the regolith [1] which it saturates and some of it percolates still deeper into the pores, joints or other openings of the bed rock, wherever it can penetrate.

The water occupying this zone of saturation is known as the *groundwater*, and forms a great reservoir of supply for many lakes, springs, and wells. All dug wells and many shallow driven wells obtain their supply from the groundwater which saturates all except the upper part of the regolith.

Water table. — The upper limit of the groundwater is known as the *water table* (Fig. 173) and agrees somewhat closely with the configuration of the land surface, but is farther from it under the hills and nearer to it under the valleys; indeed it may even reach the surface under some depressions giving rise to springs and swampy conditions (Fig. 173).

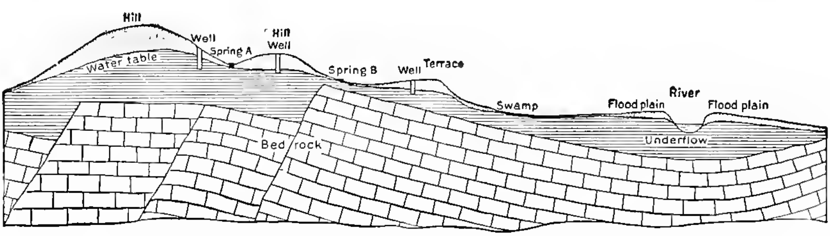

Fig. 173. — Section showing relation of water table to surface irregularities. (After Slichter. From Fuller, Domestic Water Supplies.)

The water table will show the least slope in porous sands, and the steepest slope in clays, so that in the latter it may follow the contour of the surface very closely. Under a flat expanse on a high terrace, for example, the water table may lie close to the surface, whereas near the scarp or front of the terrace it may be 50 feet below the surface.

Its depth below the surface is quite variable, being usually much nearer the surface in moist climates than in arid regions, but in any

[1] The term *regolith* is applied to the mantle of unconsolidated material, which covers the bed rock in most regions.

given area the water table may fluctuate due to different causes mentioned later.

In solid rocks there is no continuous zone of groundwater such as is found in the regolith, but the water filling joint fissures may rise to the same general level.

Above the water table there may be a zone of moist ground often several feet in thickness, into which some water is drawn from the zone of saturation by capillarity, and which is called the *capillary fringe*. It shows a greater thickness in clay, and is less thick in porous material like gravel.

Movement of groundwater. — The groundwater is not as a rule stationary but tends to move slowly from higher to lower levels; consequently its flow which is in response to gravity will sometimes roughly parallel that of the surface drainage. It thus flows down towards the valleys, where it often seeps into the channel of the stream occupying the depression, thereby augmenting its volume.

In some valleys carved in bed rock the surface stream flows in a channel cut in a filling of glacial drift or stream deposits, while the groundwater may form an underflow in this porous material, beneath the stream channel, but not always exactly coincident with it.

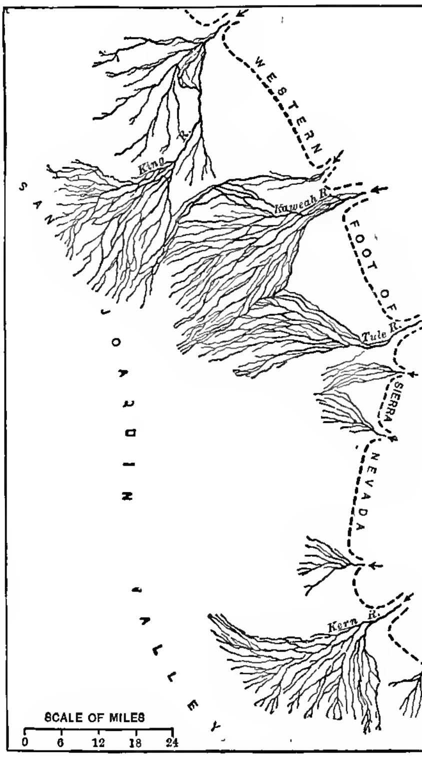

Fig. 174. — Map showing the deltas or fans of disappearing streams as they leave their mountain canyons. (After Slichter, U. S. Geol. Survey, Water Supply Paper, 67.)

Instances are known where this underflow is separated from the surface stream by more or less impermeable clay or silt layers which prevent the groundwater from uniting with the river water. We thus have at times the case of a surface stream of impure water, and below it an underflow of very good water. The latter can be drawn upon for a water supply, while the former is unsafe to use (Ref. 7).

Another type of underflow is found in some regions, where the valley floor along the foot of a mountain range is underlain by open gravel and sand deposited by swiftly-moving streams from the canyons or valleys in the foothills (Fig. 174). As these streams emerge from the hills, they flow over the surface for a short distance, and then sink rapidly into the sand and gravel, through which they travel as underground water.

Instances of the disappearance of mountain streams are common in the arid regions of the West. Many cases are found along the Coast Range in California, and they are sometimes noticed in other regions.

Rate of movement of groundwater. — In rocks having the ordinary small openings, the rate of movement is approximately proportional to: (1) Perviousness of the material; (2) difference in head per unit of distance or pressure gradient; and (3) temperature, the movement increasing with rise of temperature.

The experiments and calculations of Slichter show that with a pressure gradient of 10 feet per mile the rate of movement for different materials is as follows: Fine sand, 53 feet per year; coarse sand, 845 feet; fine gravel, 5386 feet.

Tests made by the U. S. Geological Survey in western states showed that in gravelly deposits the velocity ranged from 1 to 50 feet per day, while in similar deposits on Long Island it varied from almost zero to 100 feet per day. A maximum movement of 420 feet per day was found in some Arizona gravels. These figures of course refer to shallow groundwater, and the rate of flow would probably be considerably less in deeper and less porous water-bearing beds.

Causes of fluctuation of water table. — These may be of natural or artificial character. Natural causes are rainfall, floods, sympathetic tides, thermometric and barometric changes. Artificial causes are dams, pumping, and excavations.

Natural causes. — It is a well-known fact that the level of the water table rises during periods of rainfall and sinks during times of drought, the reason for this being self-evident, but these changes are not sudden, for it takes the soil a sensible period to absorb the rainfall and transmit it. Consequently the period of lowest or highest groundwater may lag behind that of maximum or minimum rainfall.

The water table on either side of a river normally slopes towards the stream, but if the river rises during flood, the level of the water table may be changed. But a sympathetic rise and fall of the water table will usually lag somewhat behind the corresponding fluctuations of the river surface.

The effect of sympathetic tides is perhaps less easily understood, although the action has frequently been noticed. Thus the water level in some wells in the neighborhood of the seashore seems to oscillate in harmony with the tides, rising with high tide and falling with low tide.[1]

That this vibration is in sympathy with the tides there can be no doubt, because of the facts just mentioned, and the effect has been noticed in wells from 200 to 300 feet deep, but is usually more noticeable close to the shore than some distance from it.

It is explained by supposing that there is probably a yielding clay layer, which acts as a diaphragm, and responds to the loading and unloading caused by flood and ebb tides.

Along Chesapeake Bay and its tributaries there are many wells which show tidal sympathy, some flowing only at and just after high tide.

While a clay bed often separates the salt from the fresh water, there are cases where the two are connected, and strong pumping on a well near shore may draw in some salt water.

The changes in a well level due to varying thermometric and barometric conditions have been noted at many points. Indeed, the air pressure shows a strong influence, permitting some wells to flow during low barometer, but halting the current with high barometer.

In very shallow wells changes in air temperature affect the surface tension of the water. Cold increases the surface tension; hence if some of the groundwater is near enough to the surface (within a few feet) to feel the change, it rises into the partly saturated soil above the water table under the capillary attraction of the soil particles, thus lowering the level of the water in the wells (Sanford).

Artificial causes. — It has been previously stated that the water table slopes towards the valleys, and that the groundwater flows towards them, seeping into the stream channel. If now a dam is erected across the stream channel, thus ponding the water, the water table will not sink lower than the surface of the pond or reservoir, and the spring discharge from the groundwater may be lessened, due to decreased gradient of the water table (Fig. 175).

With such conditions the crest flow of the dam may be less than the normal flow of the stream before the dam was erected. Indeed, the dam may be raised to a sufficient height to cause a flow from the reservoir into the groundwater zone.

An interesting case of this was discovered by the engineers of the Brooklyn, N. Y., waterworks at the Hempstead reservoir. Here it

[1] Veatch, U. S. Prof. Pap. 44, p. 72, 1906.

was found that the discharge was 5,600,000 gallons per day when the water was maintained at a depth of 14.35 feet, and 8,000.000 gallons when it stood at 4 feet.[1]

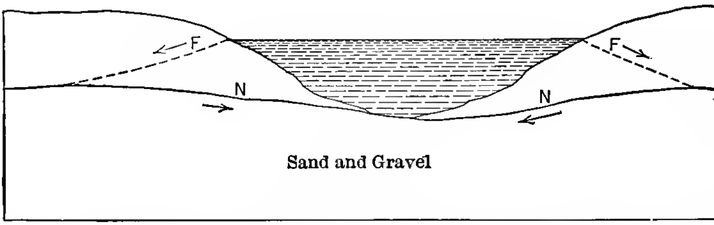

FIG. 175. — Section illustrating conditions governing movement of water away from streams or lakes. N, Normal position of water table; F, position of water table during floods. (From Fuller, Domestic Water Supplies.)

Strong pumping will lower the level of the water table in the ground surrounding a well (Fig. 176), and if the latter is near the sea, brackish or salt water is sometimes drawn in. Pumping water from mines also often affects the level of the water table in the surrounding ground, and in several mining districts drainage tunnels driven into the moun-

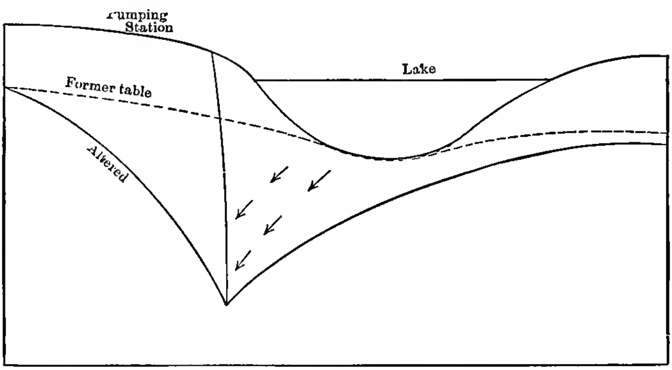

FIG. 176. — Section showing lowering of water table by pumping. (After Veatch, U. S. Geol. Survey, Prof. Pap. 44, p. 72, 1906.)

tain side to intersect the lower workings of mines produce a similar effect. The Roosevelt tunnel at Cripple Creek, Colo., was constructed with this object in view.

Digging ditches for drainage and the construction of artificial cuts for railways and highways will cause a local deepening of the water table, if they are cut below the top of the groundwater zone.

[1] Veatch, U. S. Geol. Survey, Prof. Pap. 44, p. 59, 1906.

This in some cases has resulted in draining neighboring wells, which has brought on action in court for damages.

Perched water tables. — Above the main water table small bodies of water are sometimes found, which owe their presence to local beds, or basins of clay, or other impervious material. These then hold a supply of water, and their upper limit is referred to as a *perched water table* (Fig. 184). They occasionally serve as sources of supply for shallow wells in a district where the main water table lies so deep as to be reached only by driven wells. See further under Drainage, p. 225.

Springs

A *spring* may be defined as a natural outflow of water from the ground at a single point, and from a rather definite opening. A *seepage* differs from a spring in there being no definite opening.

Springs (including seepages) show a wide variation in topographic location and volume of flow. Their flow may be continuous (*perennial*) or show only after rains (*intermittent*).

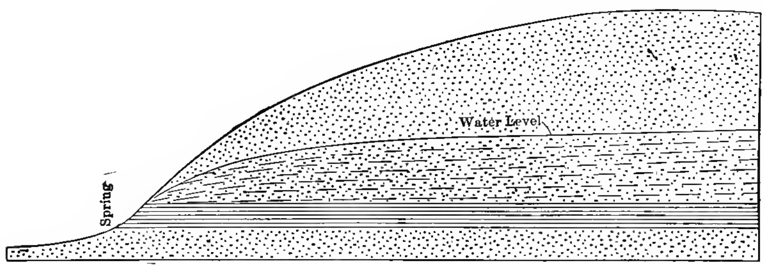

FIG. 177. — Contact spring fed from unconfined waters in porous sands overlying clay. (From Fuller, Water Sup. Pap. 255, 1910.)

Their water may be cold, in which case it is of meteoric origin, or hot, and then possibly in some cases of magmatic origin. The water of some hot springs is of meteoric derivation, the temperature being due to its having come in contact with uncooled igneous rock. The hot springs of the Yellowstone Park represent the last named type.

Classification of Springs. — The following classification of springs has been suggested by Bryan.[1]

I. Springs of deepseated origin. Supplied by juvenile or connate water admixed with deeper meteoric water. Show no seasonal fluctuation nor hydrostatic head. They include waters usually hot and more or less strongly mineralized.

[1] Jour. Geol., vol. XXVII, p. 522, 1919.

A. Volcanic springs associated with volcanoes and commonly hot.

B. Fissure springs due to fractures extending into deeper parts of earth's crust.

II. Waters mainly meteoric moving as groundwater under hydrostatic head. May fluctuate in flow with rainfall. The following subtypes are recognized.

A. Depression springs (Fig. 173) due to the land surface cutting the water table in porous rocks. Topographic location variable. Outflow usually a seepage.

B. Contact springs, emerging from a porous rock overlying an impervious one. Flow of water due to gravity, and discharge along the upper edge of the impervious rock often in the nature of a seepage. The water-tight rock may be a cemented layer in sand, a bed of clay or hard sandstone, etc. (Fig. 177).

C. Artesian springs, caused by presence of pervious beds between impervious materials. It is essential that the porous bed outcrop so as to catch the rain water, and furthermore that it be inclined. Sedimentary rocks, alternating lava flows, tuffs and gravels or clays may supply the requisite conditions. In some cases the porous bed may be crossed by a fault or joint fracture along which the water rises towards the surface (Fig. 180).

D. Springs in impervious rock, the water moving through openings of secondary origin. Two sub-types are:

1. Tubular springs, in which the water follows more or less tubular openings, such as solution channels in limestones (Fig. 179). The yield of these may be large and steady. The waters of tubular springs though of variable composition are mostly hard (p. 245), because they commonly issue from limestone, and although usually clear, they may be muddy after storms, because, unlike seepage springs, the water flows through open channels and is not filtered by percolation through sand.
2. Fracture springs, whose origin is due to water collecting in and flowing from fractures such as joints, planes of bedding, cleavage or schistosity, or even fault fractures. The flow of such springs is not as a rule large.

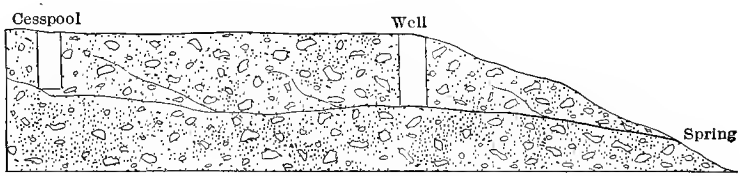

FIG. 178. — Diagram showing possibility of pollution of wells and springs by material conducted from cesspool through tubular water passages in till. (After Fuller, Water Sup. Pap. 255, 1910.)

Yield of springs. — The yield of springs is quite variable. Most of them have a limited discharge, but a group of springs harnessed together may sometimes give a considerable yield. Occasionally individual ones, especially those of the tubular type, may have a large flow.

The following figures are of interest in this connection as representing some springs of large discharge:

Silver Springs, Fla., 368,000 gallons per minute.
Comal Spring, Tex., 147,200 gallons per minute.
Warm Spring, Ore., 116,500 gallons per minute.
Giant Springs, Great Falls, Mont., 400,000,000 gallons per 24 hours.
Crystal Spring, Roanoke, Va., 5,000,000 gallons per 24 hours.

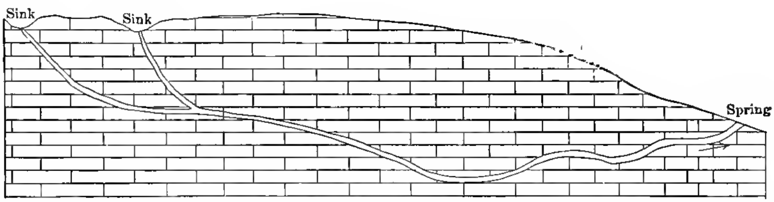

FIG. 179. — Tubular springs in limestone, the passages connecting with sink holes. (After Fuller, Water Sup. Pap. 255, 1910.)

Seepage springs, especially, do not as a rule show a steady flow throughout the year, but may dry up or greatly diminish in volume of flow during periods of drought or little rainfall.

Development of springs. — The quantity of water obtainable from springs may be increased by: (1) digging trenches or other excavations which will conduct the flow of several seepages or springs into one pool or channel and thus prevent loss; (2) enlarging the outlet of the spring; or (3) running one or more tunnels into a hillside in order to intersect the water table and thus not only increase the supply but concentrate the flow towards a single point.

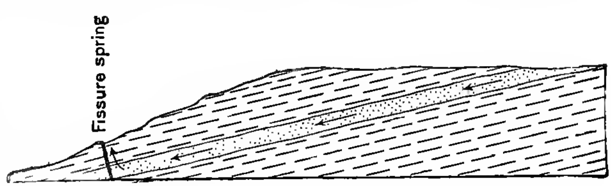

FIG. 180. — Section showing occurrence of a fissure spring. (After Fuller.)

Miscellaneous Effects of Underground Waters

Underground water is thought of primarily as a source of water supply, but it often does other work which may be a source of considerable trouble to the engineer.

Among these we may mention the relation of groundwater to landslides, tunneling operations, dam foundations, reservoir sites, railway

embankments, and limestone caves and sinks. Some of these will be taken up and cases cited.

Clay slides. — This subject is treated in some detail in Chapter VII.

Dam and reservoir foundations.[1] — In the construction of dams for reservoirs, it is essential that the foundations shall not only be solid but also water-tight in order to prevent the flow of water around the ends of the dam or underneath it.

In some cases bed rock lies so deep that the dam must be built on unconsolidated material like clay or sand. If this is not water-tight — and sand or gravel are apt to be permeable — the water either from the reservoir or ground may filter through at the sides of, or beneath, the dam, in gradually increasing quantities, so that eventually the structure is liable to give way, if proper precautions have not been taken. Dam failures due to this cause are not uncommon.[2]

The breaking of a dam or reservoir wall is sometimes caused by the giving way of the foundation rock. This may happen if shale or clay layers are present in the rock on which the dam rests.

In the case of a dam in Pennsylvania it is said that the rock consisted mainly of sandstone beds from 1 to 3 feet thick which dipped down-stream. Between these were some shaly layers 2 to 4 inches thick into which the water percolated, causing them to soften and slake. This permitted some movement of the foundation rock, which brought about the breaking of the dam.

Another case is that of the reservoir at Nashville, Tenn.

The hill on which the reservoir stands is composed of thinly-bedded and much-jointed limestone between which are layers of shale from one-half to several inches in thickness. The rocks of the hill dip quite uniformly 3 to 4 degrees, the dip being about north 25 degrees west (Fig. 181). At the point where the first break occurred there is a small fold in the rock, causing a dip of 8 degrees in the opposite direction. The wall was built on this dipping rock. Lying between the rock beds on which the wall stands are several beds of clay, the thickest of which is 10 inches, and is 4 feet below the base of the wall. This and the other clay layers had become soft due to seepage, and under the weight of the wall and the pressure of the water the rock beds broke loose along the joints of the limestone and slipped off over the slickened surface of the clay layers.

Leakage around or under a dam might be due to several causes,

[1] See under this topic in Chapter V, also U. S. Geol. Surv., Wat. Sup. Pap. 335, 1914.

[2] See Eng. Record, Apr. 14, 1912 (Oswego, N. Y.); Jan. 13, 1912 (Janesville, Wis.); Nov. 30, 1912 (Port Angeles, Wash.).

such as porous beds in glacial drift, porous rock, solution cavities, and joint fissures.

Deposits of glacial drift should be carefully examined if they are to serve as dam or reservoir foundations, because they are rarely homogeneous. If the masonry of a dam rests in solid compact till, there may be little danger of leakage, but if sand deposits are present below or at the side of the dam, seepage of water is possible. This fact was given serious consideration by the engineers in locating reservoir sites for the Catskill water-supply system.[1]

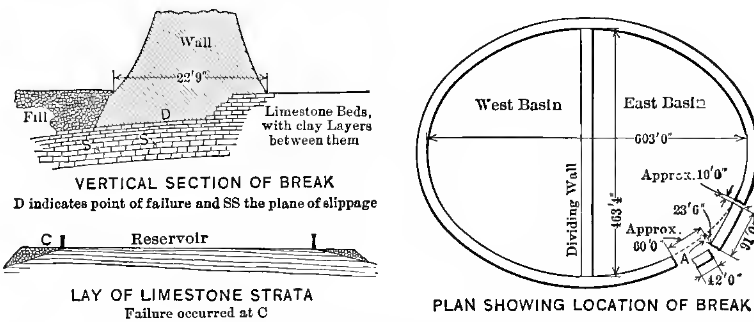

FIG. 181. — Plan and section of Nashville reservoir, showing cause of break. (After Purdue, Eng. Rec., LXVI, p. 539.)

Where volcanic rocks are abundant the porosity of the rocks is a feature that has to be given serious consideration. The porosity may be due to either amygdaloidal cavities in lavas, or it may be due to the spaces between the grains and fragments of the rock.

A specially interesting case was encountered on the Clackamas River in Oregon where the rock was a very porous volcanic agglomerate, and it was found necessary to close it up in some way. Some idea of its porosity may be gained from the fact, that when grout was forced down a 50-foot pipe under 200 pounds pressure, it flowed across a 6-foot interval to another borehole, rushed up this and spurted 30 feet into the air.[2]

No less serious sometimes is the construction of a dam in a limestone formation, for in some of these the rock is literally honeycombed by solution channels formed by underground waters.[3]

At Johnson City, Tenn., a reservoir was constructed on a hill of limestone, capped with residual clay. As usual the underlying lime-

[1] Berkey, N. Y. State Museum, Bull. 146.

[2] See also case of Zuni River dam, Eng. News, LXIV, p. 203, 1910.

[3] See case of Hale's Bar on Tennessee River, Res. of Tenn., II, No. 3, Mar. 1912.

stone surface was very uneven, and under one corner of the reservoir there was a deep cavern in the bedrock filled with clay. The settling of the clay in the cavern caused a rent in the floor on one side of the reservoir and allowed the water to escape.[1]

Limestone sink holes and caverns. — Water percolating into limestones along joints and bedding planes often enlarges them by solution of the calcium carbonate. The point of entrance sometimes becomes expanded to an opening of considerable size (sink hole) into which surface drainage and occasionally streams disappear. So too the underground passages become enlarged by solution so that the limestone may contain a network of tunnels and caverns.

FIG. 182. — Large hole formed along line of caving, Staunton, Va.

If these underground channelways become obstructed the water may stand in them, and is occasionally tapped by wells (p. 230). At other times they serve as drainage ways for surface refuse (p. 226). Occasionally their presence may be little thought of until the roof collapses.

A case of the damage caused by these solution channels was observed at Staunton, Va. Here a steep and large fissure which had been dissolved in the limestone extended beneath the town, the top of it being bridged over by a tightly-packed mass of residual clay. The fissure

[1] Res. of Tenn., III, No. 2, Apr., 1913.

contained water, and its presence, but possibly not its extent, could have been known from the fact that the water from it was pumped up through a nearby well and used for making ice.

Suddenly the clay bridge caved in for some distance at a number of places, with the result that portions of several streets and other objects were engulfed (Fig. 182).

The trouble was due to the breaking of a sewer, the water from which softened the clay cover and caused it to collapse. This in turn clogged up the fissure, caused the water in it to rise until in contact with the clay surface, and thus slake down more of it.

Tunneling operations. — In the construction of tunnels strong flows of groundwater are sometimes encountered. These may enter along joint or stratification planes, but not infrequently they follow fault planes more or less directly from the surface. The knowledge that the latter causes troubles of this sort, as well as others mentioned under faulting, should be borne in mind by engineers and be avoided if possible. (See further under Faulting, Chapter III.)

Flows of hot water, sometimes of undoubted magmatic origin, are sometimes encountered in tunnels or mine workings, but their existence cannot always be foretold. The Comstock Lode of Nevada is a classic case.

Railway embankments. — Instability of bed is frequently noticed where the road is laid on clay formations, and is often caused by spring waters which soften the clay and cause it to slide.

Foundation work. — Groundwater is often encountered in excavations for foundations, especially in low-lying land where the water table rises close to the surface. At other times subterranean channelways are cut into, which give considerable trouble, until confined. These latter are not by any means to be looked for only in limestone formations.

Drainage by Wells

Types of drainage. — There are in many regions land areas, sometimes of large size, which are so poorly drained, that they cannot be cultivated.[1]

Such tracts in the United States, for example, include swamps occupying depressions of the glacial drift in many of our northern states; swampy, flood-plain areas along the larger rivers; and swampy upland areas between streams.

Those lying close to sea level cannot in many cases be made self-draining. Others can be freed of their excess of water by: (1) Ditches

[1] Fuller, Water Sup. Pap. 258, p. 6, 1911.

leading into some stream; (2) tile pipe laid below the surface; and (3) wells.

Drainage by wells is practicable where the water is held by a perched water table in unconsolidated material (Figs. 183 and 184).

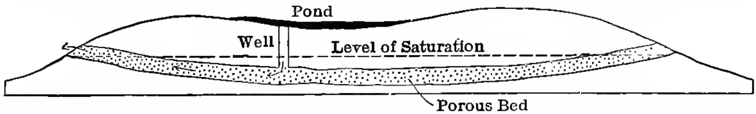

FIG. 183. — Conditions illustrating the drainage of wells into a saturated stratum of lower head. (After Fuller, U. S. Geol. Survey, Water Sup. Pap. 258, 1911.)

Drainage by wells into consolidated sediments is hardly feasible except in the case of very porous sandstones, or cavernous limestones. Fuller states that drainage into sandstone has been successfully tried

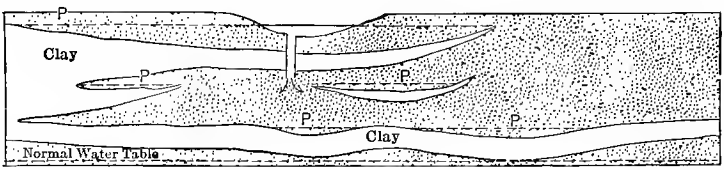

FIG. 184. — Conditions encountered by wells sunk through perched water tables. (After Fuller, U. S. Geol. Survey, Water Sup. Pap. 258, 1911.)

in Michigan, and that several wells in St. Paul and Minneapolis carry refuse into the porous St. Peter sandstone. Limestones will take up considerable water in joint and stratification planes, and if they contain solution channels their drainage capacity is still greater.

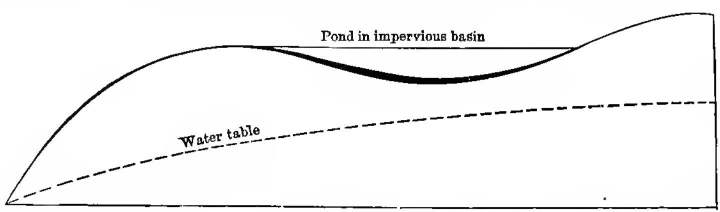

FIG. 185. — Pond held in impervious basin above the water table. (After Fuller, U. S. Geol. Survey, Water Sup. Pap. 258, 1911.)

Application of drainage by wells. — Many ponds on higher ground in the drift covered areas of Indiana, Minnesota, Wisconsin, and Michigan can be drained by wells. This has been done by driving the well either into beds of sand and gravel in the drift or into the St. Peter sandstone. In Georgia, Florida, etc., the limestone often serves as a drainage sump. At Quitman, Ga., a well is said to have drained off 1,500,000 gallons from a pond in a few hours. Cellars

have been drained by wells at Minneapolis, St. Paul, and other places in Minnesota. Industrial wastes are also disposed of in this way at some localities. In Kentucky, Georgia, Florida, and other states sewage is occasionally poured into them, and Fuller states that public or private sewage wells are in operation at Georgetown, Ky., and at Orlando, Ocala, Live Oak, Gainesville, and Lake City, Fla.

Pollution by drainage wells. — Polluted water flowing into sands and gravels will probably not do any harm beyond a few hundred feet, but in limestone passages the contaminating materials may be carried a long distance.

The use therefore of drainage wells for carrying off sewage or industrial wastes is often exceedingly dangerous, and should in the opinion of many be prevented by legislation, especially in those areas where it is likely to contaminate water supplies.

Artesian Water

Fuller has suggested that the term *artesian* be used to designate the hydrostatic principle, the tendency of water to seek its own level. Hence *artesian waters* are those which rise when beds or deposits containing them are tapped. An *artesian slope* is a slope with artesian water below it. An *artesian well* is one that taps artesian water. A *flowing well* is one in which the water rises above the groundwater level.

The artesian water contained in the rocks may gather in cavities of diverse size, origin, and shape (Ref. 3); the cavities may be spaces between the grains of either sedimentary, igneous, or metamorphic rocks; bedding planes, joint cracks (Fig. 194), cleavage planes, or schistosity planes; solution cavities (Fig. 189), breccia cavities, gas cavities in lavas, etc. From this it will be noted that some of the cavities are original ones, while others are of secondary nature.

Water capacity of rocks. — In view of the variable character of the water-holding cavities it is somewhat difficult to estimate accurately the water capacity of a rock. Moreover, any one kind of rock, such as a sandstone, may vary in its porosity.

The following figures of porosity are given by Fuller (Ref. 4).

	Per cent
Soil and loam	55
Clay	50
Sand	30
Chalk	50
Sandstone	10+
Slate and shale	4
Limestone and marble	4.5±
Granite	1
Quartzite	0.5

The porosity of a rock may depend on several factors such as: (1) The degree to which the constituent particles have been assorted as in a sedimentary rock; (2) the amount of compacting or cementation which a rock has undergone; (3) the amount of mineral matter which may have been removed in solution, thus leaving solution cavities; and (4) the amount of fracturing which a rock has undergone.

If a rock were composed of perfect spheres, of equal size, all lying in contact, the porosity theoretically would be either 25.95 or 47.64 per cent, depending on the arrangement of the particles, but few rocks show this. It is most closely approached in well assorted gravels, sands, and silts.

Amount of ground water. — Various estimates have been made to determine the amount of *free water* (as distinguished from *chemically combined water*) in the earth's crust, and they show considerable variation. Fuller estimates the total amount to be " equivalent to a uniform sheet over the entire surface with a depth of a little less than 100 feet (96 feet).[1] "

According to Delesse,[2] the amount of underground water equals 1,530,000 million million cubic yards, equivalent to a sheet of water over 7500 feet thick surrounding the earth. Slichter[3] computed the amount to be equivalent to a uniform sheet of from 3000 to 3500 feet in thickness. Van Hise[4] estimates the quantity to be sufficient in amount to cover the earth's surface to a depth of 69 meters or 226 feet. Chamberlin and Salisbury,[5] assuming the average porosity to be $2\frac{1}{2}$ per cent, estimate the amount of underground water to be equivalent to a layer 800 feet deep over its entire surface, and of an assumed porosity of 5 per cent, a layer 1600 feet deep.

Permeability and retention. — If the surface water finds its way into the open spaces of a rock and is held there by some confining agent, as a barrier of more or less impermeable rock, it will be under pressure, so that if some avenue of escape is opened up the water tends to rise towards the surface.

Since the permeability of a rock will be influenced by gravity, which is operative only in large cavities, and adhesion, which is effective only in small openings, the capacity of a rock to transmit water under pressure will depend on the size of its pores. The permeability of clay is so slow that it appears to be almost impermeable, while that of gravel is very high.

But even if the water capacity of a rock may be great, all of this water will not be available for recovery through wells. We may consequently distinguish two kinds of free water in rocks: (1) *Available* or *gravity groundwater* and (2) *Unavailable* or *attached groundwater.*

Two terms used to express these conditions are: (1) *Specific yield* which refers to the percentage of the total pore space occupied by gravity groundwater in a saturated rock, and (2) *Specific retention* which refers to the percentage of space occupied by attached groundwater.

[1] U. S. Geological Survey, Water Supply and Irrigation Paper No. 160, 1906.

[2] Delesse, Bull. Geol. Soc., France, 2d ser., XIX, 1861–62.

[3] Slichter, Water Supply and Irrigation Paper No. 67, U. S. Geol. Survey, 1902.

[4] Van Hise, Mono. 47, U. S. Geol. Survey, 1904.

[5] Chamberlin and Salisbury, Geology, Vol. I, pp. 206–207.

Requisite conditions of artesian flow. — The requisite conditions of artesian flow may be stated as follows: (1) Adequate source of water supply; (2) a retaining agent offering more resistance to the passage of water than the well opening; and (3) an adequate source of pressure.

That portion of the surface where the water-bearing bed receives its supply is known as the *collecting area.* It may be near to, or far from, the well, and of either small or great extent. The water-bearing rock is termed the *aquifer.* An area within which the artesian conditions are similar is termed an *artesian province.*

The old idea was that the conditions necessary for the accumulation of a supply of artesian water were those shown in Fig. 186, and while it may gather under these conditions they do not by any means represent the only favorable type of structure; indeed it is probable that there are few aquifers which are completely surrounded by beds of low permeability.

Aquifers, however, which are overlain by beds that retard the percolation sufficiently to produce some artesian pressure are by no means uncommon. Some counter-pressure may also be exerted by the water overlying the confining bed, but a well is not considered to have artesian pressure unless the water rises above the zone of saturation, that is higher than the water table. Indeed it rarely happens that the pressure is sufficient to raise the water much above the water table, for in most cases much water escapes through the confining beds.

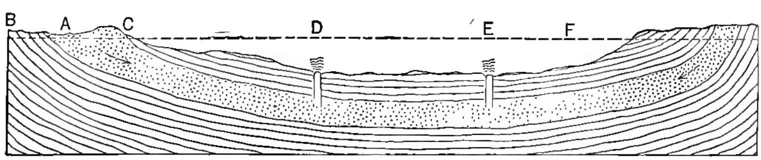

FIG. 186. — Section of an artesian basin. A, porous stratum; B, C, impervious beds below and above A, acting as confining strata; F, height of water level in porous beds A, or, in other words, height in reservoir or fountain head; D, E, flowing wells springing from the porous water-filled bed A. (From Fuller, U. S. Geol. Survey, Bull. 319, 1908.)

Artesian Water in Stratified Rocks

The simplest and most favorable structure for artesian accumulation is that which is sometimes found in stratified rocks. Thus we may have inclined beds of permeable rock capped by a bed of impermeable or but slightly permeable character (Fig. 186).

Several simple cases of this type of accumulation are shown in Figs. 186, 188, 190, and 191. In all of these the water follows the water-bearing bed and accumulates in it under pressure.

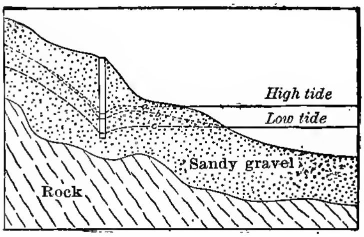

FIG. 187 — Section showing relation of tide to level of water table. (After Ellis.)

If now a well is sunk to the aquifer, the water rises in the tube and flows out at the surface, provided there is enough head, the latter being governed primarily by the difference in elevation between point of intake and mouth of well.

Sands and sandstones. — These form a great source of artesian supply. They are sometimes of considerable thickness, underlie many hundreds of square miles, and yield water under strong head.

Limestones. — Limestones are less important aquifers than sandstones, but they may yield an artesian supply under the following conditions:

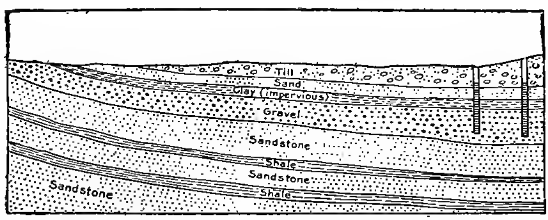

FIG. 188. — Section in water-bearing gravel with intake too low to cause water to rise to surface. (After Ellis.)

1. From joint or bedding planes, when limestone beds are included between shales or other impervious rocks; this type of occurrence is known, for example, in southwestern Ohio, Indiana, Iowa, and parts of Texas.

2. When water accumulates under head in solution channels which

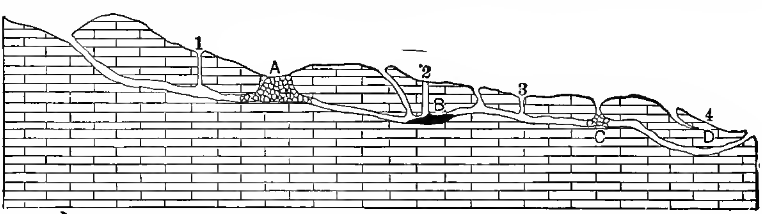

FIG. 189. — Section illustrating conditions of flow from solution passages in limestone. A, brecciated zone (due to caving of roof), serving as confining agent to waters reached by well 1; B, silt deposit filling passage and acting as confining agent to waters reached by well 2; C, surface débris clogging channel and confining waters reached by well 3; D, pinching out of solution crevice resulting in confinement of waters reached by well 4. (After Fuller, U. S. Geol. Survey, Bull. 319, 1908.)

have become clogged at some point, as by silt, or by collapse of the roof (Fig. 189).

At Lawrenceburg, Ky., a supply of water is obtained from channels and caverns in the Lexington limestone, the daily supply from four wells being given as 400,000 gallons.

Shales. — Artesian water may collect in shales, but since they are rocks of low porosity, it can accumulate only in joint or fracture planes.

Factors Affecting Artesian Water Supplies

Several aquifers in same section. — In any extensive series of stratified rocks the same kind of rock at different depths below the surface may be found occurring more than once, and so it happens that in an artesian province we may find more than one water-bearing sandstone, or both sandstones and limestones may be found in the section, all of them yielding water. They may differ in their yield and in the quality of water.

Fig. 190. — Section illustrating the thinning out of a porous water-bearing bed. A, inclosed between impervious beds, B and C, thus furnishing the necessary conditions for an artesian fountain D. (After Chamberlin.)

Fig. 191. — Section illustrating the transition of a porous water-bearing bed, A, into a close-textured, impervious one. Being inclosed between the impervious beds, B and C, it furnishes the conditions for an artesian fountain at D. (After Chamberlin.)

At Cedar Rapids and McGregor, Ia., the first wells drilled encountered salty and corrosive waters in the Cambrian sandstones; consequently, wells drilled later in these towns were stopped before they reached the horizons at which the poor waters were obtained.[1]

If a well is not properly cased, or the casing becomes pitted by corrosion, water from several different beds will flow into the same well. This sometimes accounts for a good water turning bad after the well has been in operation for a time.

Irregularities of artesian supply. — The pressure of a well will depend on the difference in level between the point of intake and the

[1] Ia. Geol. Survey, XXI, 1912, p. 150.

mouth of the well, the friction between water and rock, and porosity. The volume of flow will depend on pressure, quantity of supply, and freedom of movement of the water through the rock pores.

In any aquifer there may be dry areas, because of locally dense spots, and hence a well drilled to these will be a failure (Fig. 191). Or, a porous sandstone may grade into an impervious shale, so that if two wells were sunk to the same bed, the one striking the sandy portion would yield a flow, while that penetrating the shaly part would give none.

The exhaustion of wells may be caused by: (1) Exhaustion of water in reservoir, because it is drawn up faster than it is replenished; (2) clogging of the pores of the rock by silt or clay; (3) interference by neighboring wells; and (4) improper casing, which either allows the well to cave in or permits the water to leak away into porous strata nearer the surface.

The artesian wells of Denver, Colo., are often referred to as an interesting case of exhaustion. A few years after the discovery of this basin in 1884 there were about 400 wells sunk in an area about 40 by 5 miles. No general decrease was noted up to 1886, but between 1888 and 1890 there was a continuous decrease in the flow of the city wells, and by the end of the latter year many of them had to be pumped while others in the area were abandoned. The cause of the exhaustion was not considered to be insufficient rainfall, but rather the low porosity and consequent low-transmission power of the aquifer.

A good illustration of interference[1] was seen at Colonial Beach, Virginia, where water from a 200-foot well rose fully 20 feet above tide level. Two hundred wells followed in an area one and one-half by one mile, and as a result the head of water was so reduced, that most of the wells in the center of town do not flow at the surface, while those at lower elevations flow only at high tide.

Yield of wells. — No general statement can be made regarding the yield of wells in stratified rocks, since it varies so for different wells tapping the same formation. It has been noted, however, that with beds of the same porosity it varies with the pressure at the point of discharge.

Wells in glacial till and in many igneous and metamorphic rocks commonly yield but a few gallons per minute. A large proportion of medium diameter wells drilled to a considerable depth into sandstone, limestone, or basalt supply 25 to 100 gallons per minute, but many from such rocks yield several hundred gallons, and a few even yield over 1000 gallons.

[1] Sanford, Va. Geol. Surv., Bull. IV, 1913.

If in clean gravel at least a few feet thick, a yield of 100 to several hundred gallons per minute can often be looked for, and a few supply more than 1000 gallons. A mixture of fine material with the gravel will decrease the yield materially.

It is probable that a majority of the wells in the United States yield less than 10 gallons per minute, and the discharge of shallow wells commonly fluctuates in sympathy with seasonal fluctuations of the water table (Ref. 6).

Source of water in aquifers. — Most of the water obtained from artesian wells in stratified rocks is of surface origin, but the saline water yielded by some may be of connate character.

Fuller says:[1] "If marine beds are lifted above sea level while still in an unconsolidated condition, much of this water will drain out, except when the beds are so warped in the process as to form troughs or when drainage is prevented by the presence of overlying impervious beds."

Some wells near Wilmington, N. C., afford cases of included water in beds not yet uplifted, for flowing wells yielding salt water have been obtained at a number of points. The pressure here comes from meteoric waters which enter at the outcrop near the inner edge of the Coastal Plain sediments, and as the salt water is pumped out, fresh water takes its place.[2]

Depth of aquifer. — A water-bearing stratum dips away from the outcrop with a uniform or varying dip. In some districts wells penetrate the aquifer at not more than 100 or 200 feet depth, while in other districts drillers sometimes go to a depth of 2000 or 3000 feet to obtain a supply of water.

Artesian water in glacial drift. — Glacial deposits consist of sand, gravel, silt, clay, or a mixture of these. The first two not only have a high water capacity, but permit a rather free percolation of water, and under favorable conditions may yield flowing wells. Clays and silts are less productive.

When artesian water is found in glacial drift it is usually because pockets of sand or gravel are surrounded by less permeable material as clay, but owing to the changeable character of the drift when traced from point to point, it is rare to find the individual water-bearing materials extending for any great distance. Many small artesian basins are, however, often thickly scattered over an area, and in Michigan, for example, there are hundreds of them (Fig. 192).

Wells in glacial drift are often shallow, usually 50 to 150 feet, and

[1] U. S. Geol. Survey, Bull. 319, p. 18.

[2] Water Sup. and Irr. Pap. 160, p. 96.

the intake is often not far from the well and but slightly elevated above it. Neighboring wells may interfere to a marked degree.

Some communities of moderate size obtain their water supply from a series of wells driven in the glacial drift, and yet it is not safe to as-

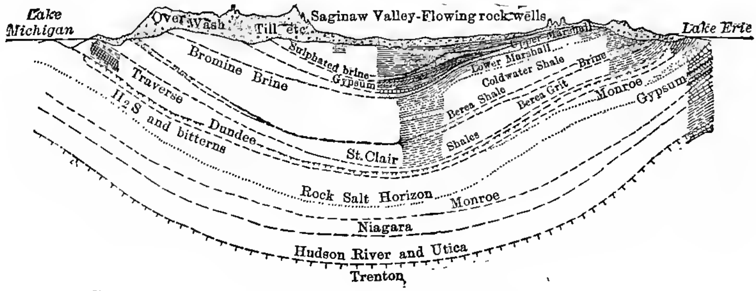

FIG. 192. — Section across Michigan, showing cover of glacial drift yielding flowing wells. (After Lane.)

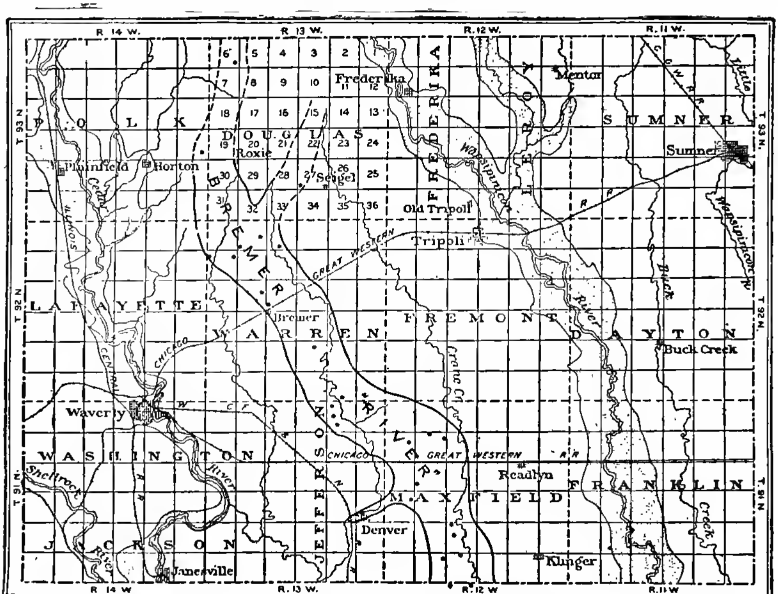

FIG. 193. — Map of artesian field of Wapsipinicon River, Iowa, and of buried channel of Bremer River. (Ia. Geol. Survey.)

sume that the volume of flow will be the same in two drift-covered regions of equal rainfall. This is because the structure of the drift in the two areas may be totally unlike. In some drift-covered regions pre-glacial river valleys (Fig. 193) are filled with drift, and a variable but good supply of water can usually be obtained from this filling.

Artesian Water in Crystalline Rocks

Crystalline rocks, in spite of their apparent density, may yield quantities of artesian water.

Engineers, who have had occasion to tunnel through such materials and encountered strong flows of water, have no doubt come to the conclusion that crystalline rocks are far from dry. But one feature that has probably impressed itself on those who have sought an artesian supply in the crystalline rocks, is that one well may be a success while a near-by one is a complete failure.

The rocks which are included under this type are the plutonic-igneous ones such as granite, diabase, etc., or metamorphic rocks such as gneiss and schist. They all resemble each other as regards their low porosity, but may be traversed by joint planes of various spacing and inclination, and it is in these that the water collects (Fig. 194).

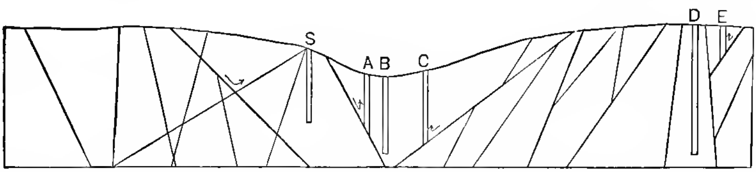

Fig. 194. — Section illustrating artesian conditions in jointed crystalline rocks without surface covering. A, C, flowing wells fed by joints; B, intermediate well of greater depth between A and C, but with no water; D, deep well not encountering joints; E, pump well adjacent to D, obtaining water at shallow depths; S, dry hole adjacent to a spring, showing why wells near springs may fail to obtain water. (From Fuller, U. S. Geol. Survey, Bull. 319.)

Since, however, most joints are rather narrow, the amount of water likely to be held in joint fissures is very moderate, and wells yielding as much as 90 gallons per minute are the exception rather than the rule.

Joints in crystalline rocks are usually very irregular, and hence the success of a well depends largely (see Fig. 194) on whether the drill hole strikes a water-bearing joint.

Some wells may strike several water-bearing joints and thus get an increased flow, but this may be lost if the hole is driven still deeper and strikes an open crack in which the water is lost.

F. G. Clapp [1] endeavored to obtain some data on the success of wells in crystalline rocks. He found, for example, that in the case of wells drilled in Maine granites, 87 per cent were successful, but that out of 72 producing wells, only 3 yielded over 50 gallons of water per

[1] U. S. Geol. Survey, Water Sup. Pap. 223.

minute. His figures also show that by far the greater number of wells drilled in granite to a depth of over 50 feet do not exceed 100 feet.

The data also show that out of 40 wells drilled to a depth of between 50 and 100 feet, 95 per cent were successful, but the percentage of successful wells decreased with depth.

Clapp concludes that contrary to the popular belief that the quantity of water will increase with depth, experience has shown that there is a far greater chance for success in wells shallower than 100 feet, while below 200 feet the chance for success decreases rapidly.

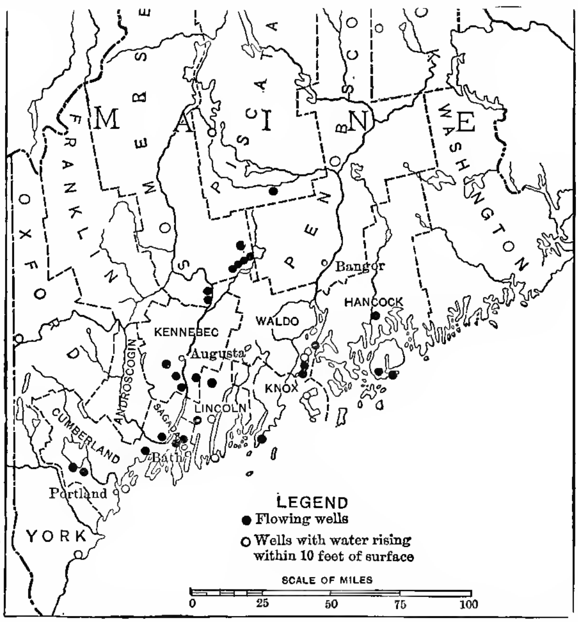

FIG. 195. — Location of flowing or nearly flowing wells of Maine. (After Bayley, U. S. Geol. Survey, Water Sup. Pap. 114, 1905.)

Sanford gives the data for 33 wells in the Richmond, Va., area, of which six have a depth of 250 feet or less, while the others range from 250 to 900 feet.

He says: " (1) Of the deep wells in crystalline rocks 5 gave 5 gallons or less per minute, making the proportion of commercially successful wells over 80 per cent. (2) Of the 22 more successful wells, 15 went less than 500 feet into ' granite ' and 1 went less than 200 feet. (3) Of the 17 wells yielding 50 gallons per minute, or over, 6 were on high ground, 6 on low ground, and 5 on hillsides, showing that yields bear little relation to the situation of wells."

Many wells sunk in crystalline rocks are not flowing at the surface, for the head is usually slight. The water, however, in most cases is of excellent quality, but those sunk close to the seashore may become contaminated by an inflow of salt water.

Irregularities in the Behavior of Wells

Both dug and deep-drilled wells often show variations in head, flow, and clearness.

Fluctuations of head. — The fluctuation in head of wells may be due to rainfall, melting of snow, freezing and thawing, and atmospheric pressure. All of these causes affect the supply of water penetrating the soil, and apply to dug wells. The atmospheric pressure will also affect deep wells, and some that require pumping during fair weather flow freely during storms.

Roiliness of well water. — Well water is usually clear, but sometimes becomes milky on the approach of a storm, which is due to small amounts of silt or clay, or iron oxide if the material suspended in the water is yellow or red.

Blowing wells. — This phenomenon, which is noticed in both drilled and dug wells, is due to a current of air which issues from them. It is sometimes strong and very noticeable.

Breathing wells. — Blowing usually alternates with sucking, and wells which show both expulsion and drawing in of air are called breathing wells, but the indraft is often overlooked because it is not as conspicuous as the outdraft. In moist climates blowing is commonly strongest before storms, and sucking in clearing weather, and thus they show a relation to barometric pressure.

Freezing of wells. — In the northern states especially, much trouble may be caused by the freezing of both dug and drilled wells, more particularly the deeper drilled ones. Indeed some wells in the North are kept from freezing only with great difficulty.[1]

In open wells cold air can enter and freezing may occur, but in covered dug wells there is usually little trouble unless the water level is near the surface, and the same is true of the simpler type of driven wells with single continuous casing or double tubes, which are carried below the groundwater level. (Fuller.)

Most of the wells subject to freezing are the drilled or double-tube wells, in which the inner pump tube is carried below the outer casing, and stops in some porous stratum, or in solution passages in limestone. Cold air flowing down the casing or through the fissures in the rock freezes the water in the well tube.

According to Fuller the wells of Maine, for example, many of which are in granites, slates, shales, and other hard rocks free from openings, give no trouble by freezing. On the other hand, in Minnesota, North Dakota, and Nebraska many wells penetrate porous deposits or cavernous limestones and freeze every winter. Even in Pennsylvania freezing sometimes occurs in oil wells at a depth of several thousand feet.

Cause of preceding phenomena. — It seems quite evident that fluctuations of head and flow, breathing, freezing, etc., are all referable to a single cause, i.e., barometric pressure.

Thus freezing, indraft, depressed water level, decreased discharge, and clear water appear to accompany a high barometer; in other words, increased atmospheric pressure.

Thawing, blowing, increased head, and milkiness all accompany a low barometer or decreased atmospheric pressure.

To illustrate: If the barometric pressure is low, the water may flow from the well more rapidly, and the increased velocity of flow may carry clay or silt out of the pores of the rock causing roiliness of the water. During high barometer in cold weather the cold air is forced down the well hole and produces freezing. The remedy for this is to seal up the top of the well and prevent the ingress of air as much as

[1] Fuller, Water Sup. Pap. 258, 1911, p. 23.

possible. In limestone where solution channels afford a by-pass to the cold air, the well may need packing from top to bottom.

Temperature of well waters. — The temperature of well waters varies somewhat although the majority of wells whose temperature has been determined range between 55° and 75° F. Some fall considerably below this and a few exceed 100° F. A large number of records have been tabulated by Darton.[1]

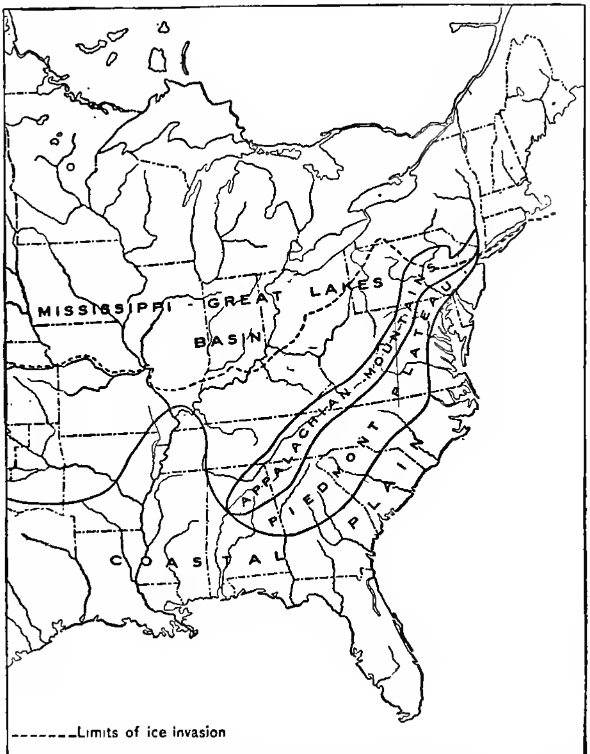

FIG. 196. — Geologic and water-supply districts in eastern United States. (After Fuller, Water Supply Paper 114, 1905.)

Groundwater Provinces of the United States

Groundwater supplies are found in many parts of the United States, but owing to the diversified character of the water-bearing materials and variations in geologic structure, the manner of occurrence of water is not the same.

There are, however, a number of individual areas, some of them of

[1] U. S. Geol. Surv., Bull. 701, 1920.

large size, throughout each of which the groundwater conditions are somewhat similar and are known as *groundwater provinces.*

In the United States the following important provinces at least may be mentioned.

1. Drift Area; 2. Weathered Rock Area; 3. Coastal Plain; 4. Piedmont Plateau; 5. Appalachian Mountains; 6. Mississippi Basin; 7. High Plains, 8. Rocky Mountains; 9. Great Basin; 10. Pacific Coast Belt.

The underground water conditions in these are briefly as follows:

Glacial drift province. — This includes that portion of the United States covered by the glacial drift, which consists of two main types, viz., till and modified or stratified drift (Chapter X).

Both dug and artesian wells may obtain a supply of water from glacial deposits (p. 311). Indeed there are hundreds of artesian wells drawing water from the glacial drift, but most of them are of only moderate depth and for private use.

Occasionally a sufficient supply is obtained for municipal purposes.

Weathered Rock province. — South of the glaciated area the bedrock, especially in moist climates, is often covered by a mantle of decayed rock. The soil is more or less clayey, often red or yellow in color, and contains fragments of disintegrated rock. While the material holds considerable water, it is of little value, except as a source of supply for shallow wells. Over many areas the water is usually of good quality but necessary precautions must be taken against possible sources of contamination.

In the same regions there may also be local deposits of alluvial material as in river valleys, which may be water bearing.

Atlantic Coastal Plain. — This strip of territory (Fig. 196) extends from Long Island, N. Y., to the Gulf States. Its surface is generally flat, and does not rise to more than from 100 to 500 feet above sea level, but the major streams have cut fairly deep valleys.

The materials underlying the plain are clays, sands, and gravels, with occasional porous sandstones and limestones, the last two being more abundant in the Southern States. The whole series of beds dips gently seaward.

At the northern end of the plain the waters are chiefly in sands and gravels, especially those near the base of the formation, but farther south, and more particularly in the Gulf States, the sandstones and porous limestones also serve as aquifers.

The water in the sands and gravels at the north is said to be generally soft and good, but farther south, where limestone beds occur, the water is often hard and charged with sulphur and iron.

There are several thousand wells scattered over the Coastal Plain, and many of them are of large capacity and flow without pumping. They are used chiefly for domestic and farm supplies and also manufacturing plants, but some towns utilize them for municipal supplies.

Piedmont Plateau province. — This province (Fig. 196), which extends along the eastern front of the Appalachian Mountains from southeastern New York to Alabama, is composed chiefly of crystalline rocks with a few small areas of Triassic sediments.

The plateau joins the Coastal Plain along the Fall Line on the east, and there has an elevation of not more than a few hundred feet, but gradually rising west toward the rolling surface attains a height of several thousand feet in western North Carolina.

With the exception of sandstones and shales in the Triassic basins, the rocks are mostly schists, gneisses, and granites; hence the distribution of artesian waters is relatively uncertain, since they accumulate mainly in the joint planes and similar spacings of the rocks. However, the waters are usually good, and at times are rather strongly mineralized.

They are used mainly for domestic and farm purposes and in small industrial establishments, while the towns and cities depend chiefly upon the surface streams for their needs.

Underground water conditions similar to those in the Piedmont Plateau are found in the crystalline rock areas of New York, New England, Minnesota, and Wisconsin.

Appalachian Mountain province. — This province (Fig. 196) extends from eastern Pennsylvania to Alabama, and might also be said to include the Berkshire Hills of Connecticut and Massachusetts, and the Green Mountains of Vermont.

The rocks, which consist of quartzites, sandstones, limestones, and shales, are strongly folded and faulted. Both the limestones and sandstones may contain much water, but it is rarely used, even though the synclines sometimes give flowing wells.

Deep wells are rare, as there are only a few large cities in the belt, and the main reliance is placed on surface streams and springs.

Mississippi-Great Lakes basin. — In this province artesian water is obtained mainly from sedimentary rocks, except around Lake Superior where the rocks are mainly metamorphic. The St. Peter and St. Croix sandstones have a large collecting area in Wisconsin (Fig. 197) and dip southward under Illinois and Iowa, where to moderate depths they supply good water. The Berea sandstone yields water in Ohio, while the Corniferous and Onondaga limestones are important in the same state. The Niagara limestone is an aquifer in Indiana and Wisconsin.

High Plains province. — Within this province is included a great area, which extends eastward from the eastern edge of the Rocky Mountains, and includes a large part of North and South Dakota, Nebraska, Kansas, Oklahoma, and Texas.

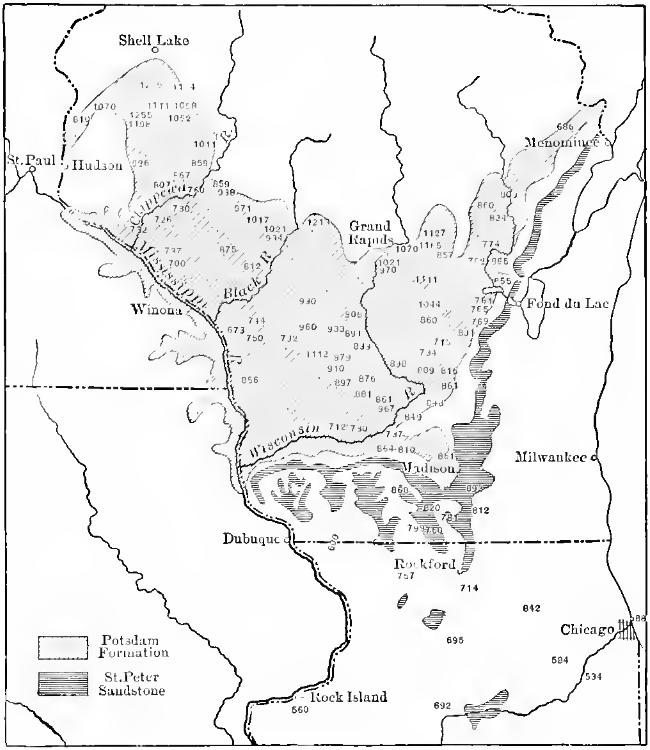

Fig. 197. — Wisconsin outcrop of Potsdam and St. Peter sandstones. Figures indicate height in feet above mean sea level. (After Slichter, U. S. Geol. Survey, Water Supply Bulletin, No. 67.)

In this area the Dakota sandstone which outcrops on the flanks of the Rocky Mountains and around the Black Hills (Fig. 198) forms an important water-bearing formation under the western part of the High Plains, giving flowing wells often in the valleys.

Farther east the Dakota sandstone lies too deep, and the formations higher up in the series have to be drawn upon. Many of the underflows in the gravels are also tapped. Some of the limestone beds, especially in Texas, yield good supplies of water.

Rocky Mountain province. — In this province the rocks of the different ranges are much disturbed by folding and faulting, and no

important artesian systems exist. Many good springs, however, are found in the mountains, and the valley gravels may also yield an excellent supply.

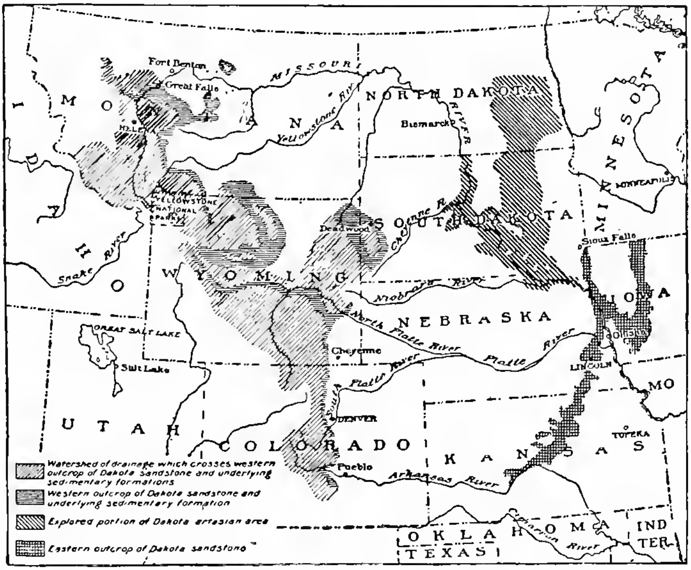

FIG. 198. — Darton's map of catchment area of the Dakota sandstone and the Dakota artesian basin. (After Slichter, U. S. Geol. Survey, Water Supply Paper, 67.)

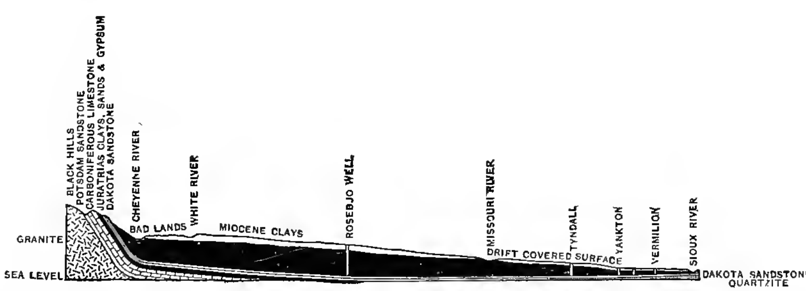

FIG. 199. — Section from Black Hills to eastern South Dakota, showing structure of artesian basin. (After Darton.)

On the western edge of the Rocky Mountains, facing the Great Basin, the gravels washed out by the mountain streams often hold much water.

Great Basin province. — In this region, which lies between the Rocky Mountains and the Sierra Nevada, the basins between the ridges are often filled to considerable depths with sands and silts, or

gravels which are partly stream deposits and partly wash from the valley slopes.

The rainfall is small, and much of the water courses down the bare slopes to soak into this basin filling. While in many parts of the region the water level lies far below the surface, still in some localities a good supply is encountered, especially in Utah, Arizona, and southern California. Some of the deeper California waters are said to be under sufficient head to yield flowing wells, suitable for municipal, ranch, and irrigation purposes.

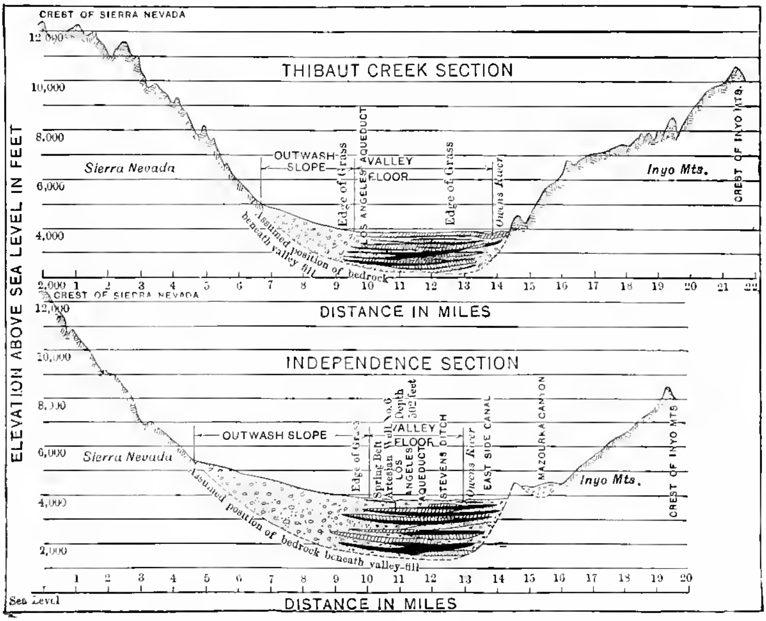

FIG. 200. — Sections across Owens Valley, Calif., showing unconsolidated beds in which the groundwater accumulates. (After Lee, Water Sup. Pap. 259, 1912.)

The vast lava beds of eastern Washington and Oregon, and of Idaho, form an important aquifer in this province.

A typical case of an underground reservoir in a desert region is to be found in Owens Valley of east central California. This is a closed rock basin about 120 miles long, which is bounded on the west by the Sierra Nevada, and has practically no subterranean outlet.

The porous valley fill (Fig. 200), which consists of clay, gravel, sand, and boulders, has in places a depth of as much as 2500 feet, and forms an immense underground storage reservoir which absorbs much of the water that flows down from the eastern slopes of the

Sierras, while Owens River carries off the excess that is not absorbed, and delivers it to Owens Lake.

The city of Los Angeles has developed a water supply from the surplus surface waters reaching the lower end of the valley and from the underground sources.[1]

Pacific provinces. — This includes several sub-provinces, such as the Sierra-Cascade, Central Valley, Coast Range, and Pacific Coastal Plain. The Sierra-Cascade and Coast Range are similar to the Rocky Mountain province.

Much moisture, which is condensed by the peaks of the Sierra and Cascade mountains, flows down the slopes to the gravels at the base, and from these into the alluvial deposits of the Central Valley. Here it forms an important supply of underground water.

In the Pacific Coastal Plain there are deposits of considerable thickness which are strong water bearers in southern California, around Puget Sound, and at several other points.

Composition of Groundwaters [2]

Introduction. — All groundwaters contain a greater or less quantity of suspended or dissolved matter. The former may consist of clay, leaves, or bacteria; the latter of mineral substances, obtained in part from the rocks or soils through which the water percolates, its solvent power being increased by the presence of organic acids derived from the soils or other acids obtained from the air.

The water may thus obtain soda and potash from feldspars; calcium and magnesium from limestones, etc.; or iron oxide, alumina, and silica from different minerals of the soils and hard rocks.

But the quantity of mineral matter which the groundwater dissolves will depend also on the grain area exposed, the underground pressure, and the rate at which the water is moving through the rocks.

As a result we find that groundwaters differ greatly in the kind and amount of mineral matter which they carry in solution, and upon this depends the usefulness of the water for one purpose or another.

The amount of mineral matter in solution is usually expressed in parts per million.[3] (See further under Rivers, Chapter V.)

Relation of rock material to dissolved matter. — Since many sands and gravels consist chiefly of silica, they may show only a few parts

[1] U. S. Geol. Survey, Water Supply Pap. 294, 1912.

[2] See further regarding composition of water in Chapter V.

[3] One liter of water weighs 1,000,000 milligrams, and therefore 1 milligram or 0.001 gram of solids per liter of water is equivalent to one part per million. To get grains per United States gallon, from parts per million, divide by 17.1, or from grams per liter, by 0.0171.

per million of dissolved mineral matter, although in desert sands and gravels the amount of alkaline and calcareous material may be large. Some sands and gravels may contain soluble mineral grains or other soluble impurities, which succumb to the attacks of the water filtering through them.

Fine-grained materials, like clay, expose considerable surface to solution, and the waters in them may be much more strongly mineralized than those in sand and gravel; indeed, some are so alkaline or calcareous as to be unfit for boiler use.

Waters in both sandstones and slates are somewhat more mineralized than in those materials mentioned above, probably because they contain more cementing material than sands and clays, but the crystalline rocks contain still less, since the water circulates mainly in joint planes, and hence has comparatively little solution surface to work on.

Limestones give more soluble matter than any of the other rocks, as the carbonate of lime is rather easily soluble, and the waters from the softer ones often carry hydrogen sulphide.

Effect of mineral ingredients. — This has been discussed under Rivers, Chapter V.

Potable water. — The ordinary mineral ingredients of underground water, such as calcium, magnesium, silica, iron oxide, etc., are usually harmless in the quantities commonly present, but any constituent which is abundant enough to taste is bad.

Some are so strongly saline as to be unfit for use; others contain hydrogen sulphide which gives the water an unpleasant taste and corrodes metal. Not a few contain enough iron to be noticeable to the taste.

Abnormal amounts of chlorine in waters which have traveled but a short distance from the surface indicate pollution, but the test is less important in deep waters, as these may gather considerable chlorides from the rocks. Nitrites indicate decomposing organic matter, and nitrates such material already decomposed.

Suspended matter. — The suspended matter found in surface waters may be of animal, vegetable, or mineral character. That which is very fine-grained can be carried into the pores of the soil and rocks, but unless these openings are fairly large, the suspended matter even if fine is not likely to be carried for a great distance.

Suspended animal and vegetable matter is not so common in well waters, but finely-divided sand and clay are not rare.

For industrial purposes, where the water is used for washing or comes in contact with food materials, suspended matter is objectionable, for

it is likely to stain or spot the product. If the suspended animal or vegetable matter is liable to decomposition or partial solution it is even more objectionable, when in small amounts (10 to 20 parts per million), than are equal quantities of mineral matter.

Color. — The color of water is due mainly to dissolved vegetable matter, and where it is to be used for bleaching, dyeing, or paper making, any discoloration is undesirable. Color causes serious objection only when the vegetable matter in solution exceeds 20 or 30 parts per million.

Pollution. — Groundwaters percolating through the interstices of rocks often have suspended matter filtered out, slower filtration being more effective than fast.[1] Bacteria may also become entangled in the sediment. Both oxidation and bacterial action may serve to break down organic polluting materials, and also destroy disease producing organisms.

Where however the groundwater flows through more open channels, as in limestones, pollution may be carried for some distance.[2]

Pollution of wells is sometimes due to contamination entering along defective casings.

References on Underground Waters

General. — 1. Bowman, U. S. Geol. Surv., Wat. Sup. Pap. 257. (Well drilling methods.) 2. Fuller, Wat. Sup. Paper 255, 1910. (Underground waters for farm use.) 3. Fuller, U. S. Geol. Surv., Bull. 319, 1908. (Factors controlling artesian flows.) 4. Fuller, Domestic water supplies for the farm, New York, 1912. (Wiley & Sons.) 5. Keilhack, Lehrbuch der Grundwasser und Quellenkunde, Berlin, 1912. (Gebrüder Bornträger.) 6. Military Geology, Chapter on Water Supply. New Haven, 1918. (Yale University Press.) 7. Slichter, U. S. Geol. Surv., Wat. Sup. Paper 67, 1902. (Underground waters.) 8. Woodward, Geology of Water Supply (London, 1912). 9. Lapworth, Assn. Water Engrs. (Eng.), June, 1911. (Geology dam trenches.)

See also many bulletins on Water Supply and Irrigation issued by United States Geological Survey, and special reports on underground waters by the different State geological surveys.

[1] U. S. Geol. Surv., Wat. Sup. Papers 255, 256, and 258.

[2] U. S. Geol. Surv., Wat. Sup. Papers 233 and 258.

CHAPTER VII

LANDSLIDES, LAND SUBSIDENCE AND THEIR EFFECTS

Landslides

Definition. — Under this term are included all downward and often sudden movements of surface clay, sand, gravel, and even solid rock. The movement is in response to gravity, and, in the case of unconsolidated materials at least, is often aided by the fact that the material has become water-soaked and is very mobile.

Landslides are frequently referred to in a casual manner in geological textbooks, and their destructive effects are sometimes commented on, but it is doubtful if their full importance as a factor in applied geology is always realized; moreover, in the minds of many their occurrence is commonly associated with mountain districts.

The slow creep of soil down the hillside, the sudden rush of rock or unconsolidated material down the mountain slope, or the slide of soft mud below the water surface, all interfere from time to time more or less seriously with engineering operations, and consequently it is of importance for the engineer to know something about them.

Although the presence of water in the rocks and soils is often a powerful factor in initiating a landslide, still in some cases earthquake shocks have played an important rôle in dislodging the masses of moving material.

Classification of Landslides

Several rather distinct types of landslide have been recognized. The several types will be taken up, and examples of each given as far as possible, together with a statement of the trouble they have caused.

Creeping slides. — This type includes those slow, downward movements of soil or other unconsolidated material, which are commonly referred to as *creep*. They may originate on any slope except one of very low angle, and involve not only soft clay and sand, but also the angular rock fragments of talus slopes.

Where steeply-dipping rocks crop out on a hillside, the upper portions of the layers are sometimes bent over by the general down-slope

movement of surface material, so as to give the impression that the dip is in the opposite direction from what it really is.[1]

These slow, creeping slides, while not as disastrous in causing loss of life as rapid ones, nevertheless often give much trouble.

A railway track laid across them has to be re-aligned from time to time because the slow movement of the soil or talus material displaces it. The same thing often happens where railroads cross clay slopes, but here the case is sometimes aggravated by the clay swelling when it absorbs water. Tunnels or mine shafts penetrating material of this sort are also likely to be thrown out of line or even squeezed together.

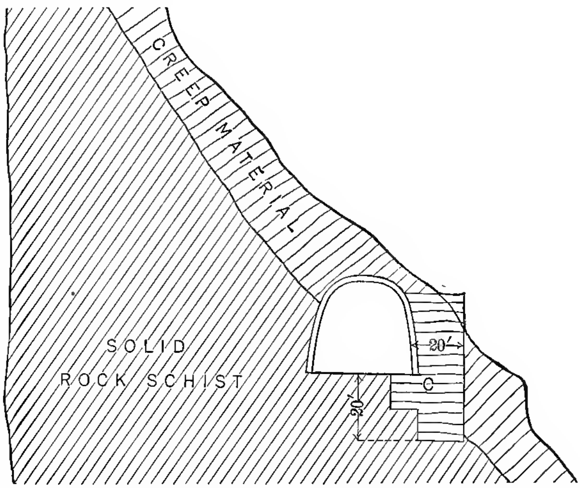

FIG. 201. — Section showing position of Mühlthal tunnel and creep material on Brenner Railroad. (After Drinker, Tunneling.)

Drinker [2] states that there have been many cases of landslides by which parts of railroads located along mountain-slopes have been displaced, and that sometimes tunnels have been affected, one of the most noted examples being that of the Mühlthal tunnel on the Brenner Railroad in Europe (Fig. 201). The rock was an argillaceous schist requiring blasting, and where the slide occurred the tunnel was very near the surface. "During the building it was observed that the hillside had been shaken, and finally it became necessary to break through the side walls, and sink shafts down some 20 feet to solid rock all along the damaged section, and a heavy retaining wall was then built up."

[1] See U. S. Geol. Survey, Prof. Paper 56, Plate VII, p. 60, 1907, for a good case.
[2] Tunneling, 1878.

The foundations of buildings built on a creeping surface may be similarly affected.

Slides of unconsolidated material, of swift movement. — The slides of this type differ from the preceding one in being of greater magnitude, but mainly in the more sudden and violent character of the slide which may be either hard or soft material. The angle of slope is not necessarily steep, or the point of starting necessarily high above the surrounding country (Fig. 203).

Common examples of this type are the frequent dirt and rock slides that move down the slopes in some mountain regions, cleaning out the vegetation in their path and leaving a bare scar on the mountain side. Such a mass may cling to the mountain slope for a long time until loosened by frost, or softened and soaked with rain water, when it comes down suddenly and without warning.

Clay slides of considerable magnitude are not uncommon. The movement may be due to: (1) The bank as a whole becoming so water soaked as to lose its coherence; (2) certain layers becoming wet and slippery so as to act as a slipping plane for the overlying material; (3) water seeping over a smooth and usually inclined rock surface on which the clay rests; (4) some bed in a section becoming so softened by water as to collapse under the weight of the overlying beds; or (5) a combination of these causes.

It should be remembered, however, that it is not necessary for the moving material to rest on a steeply-sloping surface, in order to slip. On the contrary large areas of clay land have sometimes moved downward with almost irresistible force over comparatively gentle slopes.

A good case is that of a slide which occurred on the Liévre River, north of Buckingham, Quebec (Fig. 202). Here there was a clay terrace resting on a glaciated rock surface. The clay had become so thoroughly water-soaked after a period of rain, that an area of about 100 acres slid into the river. But so great was the pressure, that the clay was pushed entirely across the stream, which had a width at this point of six chains, and masses of it were pushed up on the east bank to a height of from 20 to 30 feet.[1] In addition a tongue of the clay moved up-stream and displaced a crib-work dam, pushing it at least 100 feet.

This is not an uncommon phenomenon in valleys where clay terraces rise above the river level, and many of them have occurred, for example, in the Hudson River Valley of New York State.[2]

While slides of this sort are likely to occur when the clay becomes

[1] Can. Geol. Survey, Ann. Rept., Vol. XV., Part AA, p. 136, 1904.

[2] Newland, Eng. Rec., Aug. 28, 1915, and Eng. News., Aug. 12, 1915.

water-soaked, still their descent is sometimes hastened by any cause which steepens the face of the bank. Thus the undercutting of a clay deposit by a stream, or any artificial excavation which gives a steep face, leaves the bank without proper support and invites a slide.

Some years ago, the brick pits at Haverstraw, N. Y., were worked towards the city, leaving a steep and high face, which resulted in a portion of one of the streets and a number of houses sliding into the excavation.

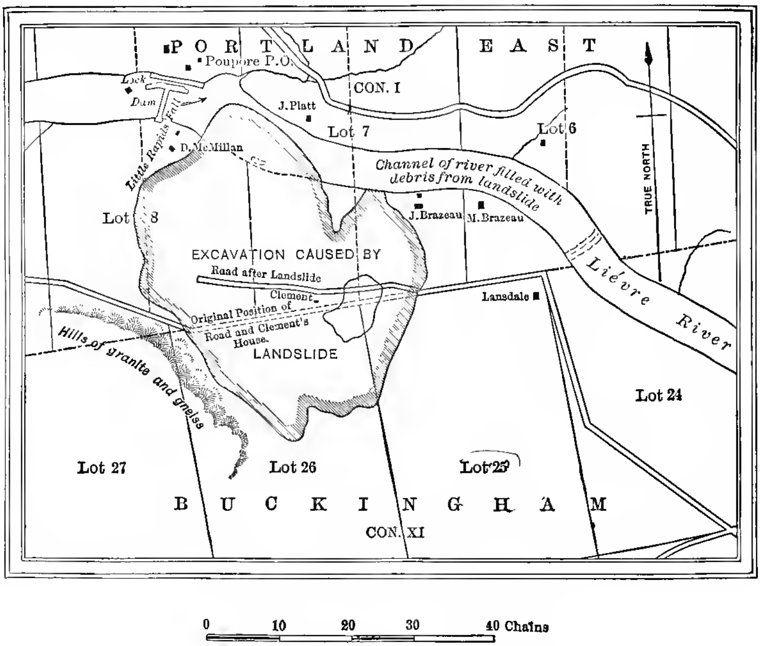

FIG. 202. — Map of slide on Liévre River, Que. (After Ells, Can. Geol. Survey, XV. Pt. AA, 1904.)

Engineers in making railway cuts through clayey material sometimes overlook the tendency of the moist clay to slide, which is sure to occur if the angle of the embankment is too steep. Drainage of the clay sometimes prevents it. Where towns are located on terraces underlain by such materials, some means should be taken to retard the slipping of the banks, for if it goes on unrestrictedly, the face of the cliff often slowly but surely recedes. Shales which slake down easily are apt to slide almost as readily as clay.

The Panama canal has furnished fine examples of clay slides (Ref. 5) some of which are influenced by the rock structure.

The rocks underlying the table land cut through by the canal consist of a series of clays, shales, sandstones, conglomerates, limy sands

Fig. 203. — Slide of clay caused partly by undermining action of stream, and partly by clay becoming water-soaked. (H. Ries, photo.)

and interbedded tuffs and lava flows. These are gently folded, and in places faulted, and in the area of the deepest part of the canal cut,

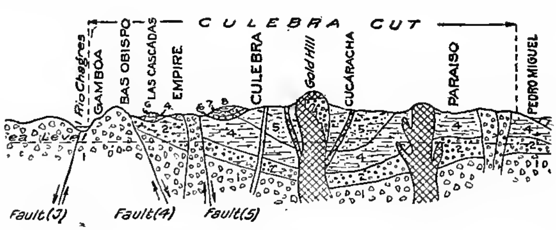

Fig. 204 — Generalized geologic section through Gold Hill. (MacDonald, Bur. Mines, Bull. 86, 1915.)

form a great syncline (Fig. 204). This syncline is cut by several massive intrusions of basaltic rock of relatively strong character which project above the general level of the table land and form Gold Hill and

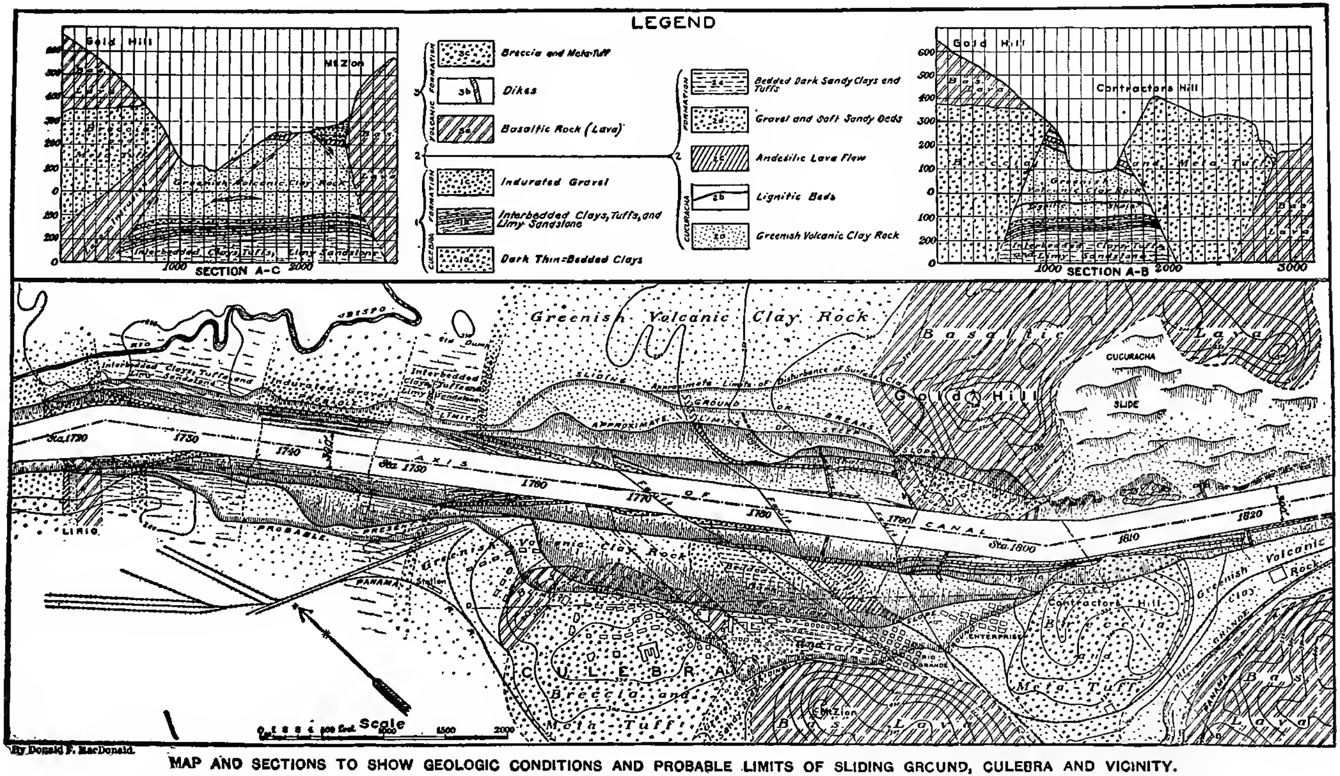

Fig. 205. — Map to show geologic conditions and probable limits of sliding ground, Culebra and vicinity. (MacDonald, Bur. Mines, Bull. 86, 1915.)

Contractor's Hill. On either side of them and extending down towards the base of the cut is the Cucuracha formation which consists of massive and locally bedded, slightly indurated clay rock of andesitic composition. There are also local red clay beds, and sandy and gravelly lenses. The formation is broken by many small faults, and is extensively altered, containing a high percentage of chloritic material which makes it very slippery. It is therefore evident that if material of this nature becomes saturated with water it will slide readily if unsupported. Considerable water soaks into the clayey rocks during the rainy season. The excavation of the canal naturally left the water-soaked clay on either side unsupported and it began to slide, continuing this for some time, and gradually extending the area of disturbance to some distance from the canal (Fig. 205). Since Gold Hill and Contractor's Hill were of massive rock, the slides were restricted by these.

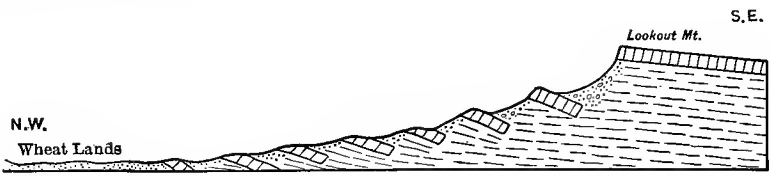

FIG. 206. — Ideal profile of landslides on the northern side of Lookout Mountain, Wash. (After Russell, U. S. Geol. Survey, 20th Ann. Rept., Pt. II.)

Sliding of material of this nature is not likely to cease until it has reached a very low surface slope.[1]

In some cases a slide is precipitated by a soft, porous bed at the bottom of a cliff giving way, as in the Cascade Mountains in northern Washington,[2] where the Columbia lava, in sheets 400 or 500 feet or more thick, rests on clays and sands, or on deposits of volcanic lapilli, the series having been eroded so as to form steep escarpments. . . . Many examples of these conditions are furnished along the great northward-facing escarpment of Clealum Ridge, and on the western margins of the sloping table-lands known as Lookout and Table Mountains. (Fig. 206.) Throughout this irregular line of great escarpments the landslides that have occurred are to be numbered by the hundreds.

Rock slips. — These are restricted to cases where stratified rocks have a dip in the direction of the slope of the hill of which they form

[1] See also case of Slumgullion mud flow, Howe, U. S. Geol. Surv., Prof. Pap. 67, 1909.

[2] Russell, U. S. Geol. Surv., 20th Ann. Rept., Pt. II, p. 193, 1900.

a part. Slipping is therefore initiated along the bedding planes of a rock.[1] Cleavage planes might produce the same type of rock slip.

Slips of this type are likely to start from artificial causes. Thus, for example, if the stratification or cleavage planes dip towards the face of a slope, the removal of stone for quarrying,[2] or for road and railway cuttings, leaves the material unsupported (Fig. 207). If a slide does not occur at once, it is very likely to take place later when water and frost get into the mass.

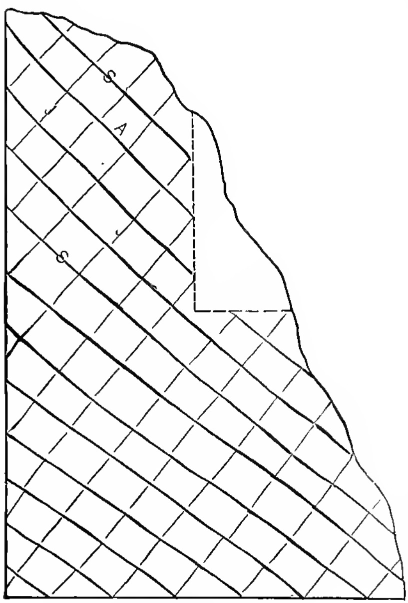

FIG. 207. — Section showing structural conditions likely to produce rock slides along joint or stratification planes.

Belonging to this type also are the interesting Rock Streams of the San Juan Mountains of Colorado (Ref. 4). Many of the high glacial cirques of the San Juan Mountains are covered by enormous masses of rock débris resembling in its general appearance ordinary talus, but the form of these accumulations is quite unlike that of the long, even slopes of detritus at the base of cliffs. These masses closely resemble those of landslide origin in their general form and in their relation to the points from which the material has been derived.

One of the largest is from 50 to 100 feet thick, three-quarters of a mile long, one-third of a mile average width, and has a minimum estimated mass of nearly 13,000,000 cubic yards. The material is volcanic rock derived from the neighboring cliffs.

Rock falls. — These may take place regardless of the character or attitude of the rock mass. A fine example of this type was the rock fall that occurred at Frank Alberta (Ref. 3), in 1903 (Figs. 208 and 209). This was due to the breaking loose of a great mass of rock, about one-half mile square, and from 400 to 500 feet thick, from the top of Turtle Mountain. The latter towers about 3000 feet above the

[1] See, for example, slipping of bridge piers in a slippery clay over coal seam, Eng. News, XXXIX, p. 278, 1898.

[2] Geol. North Derbyshire, Mem. Brit. Geol. Surv., 1887, p. 83.

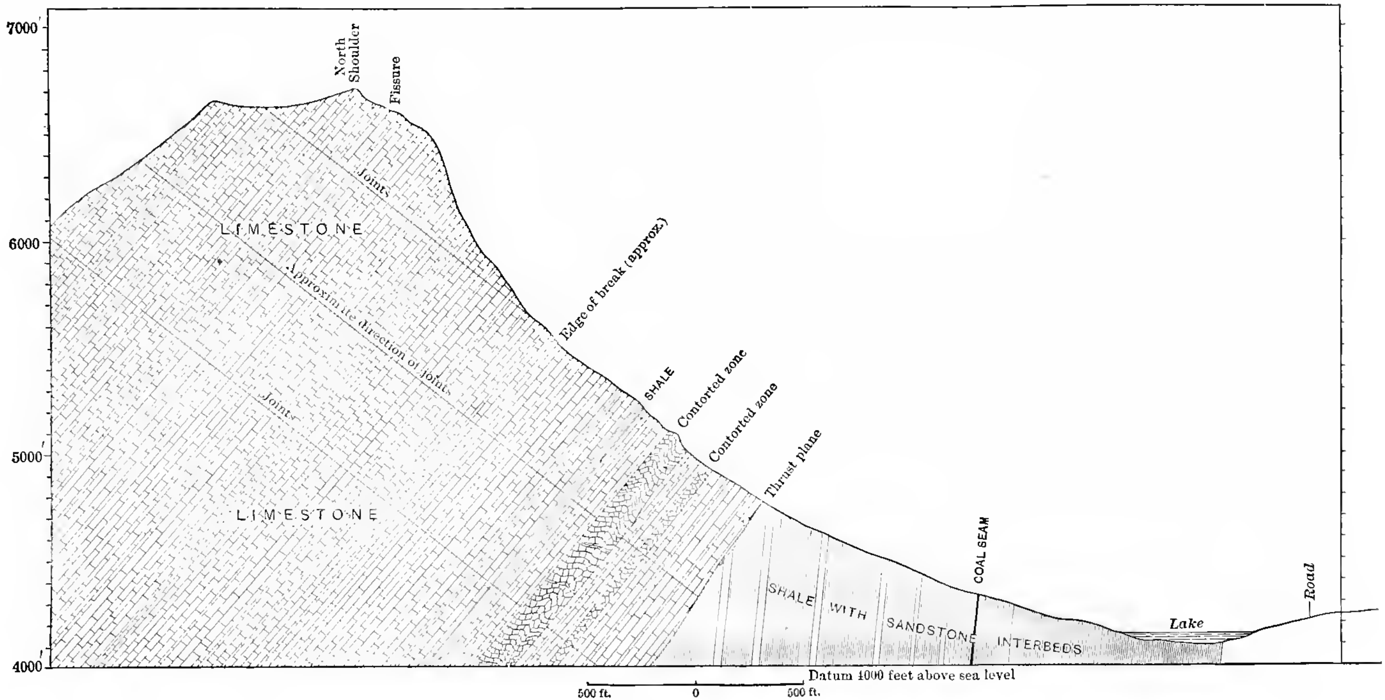

FIG. 208. — Section through Turtle Mountain, Frank, Alberta. (Can. Geol. Survey.)

valley of Oldman River in which the coal-mining town of Frank is situated.

Turtle Mountain consists of westerly dipping limestones in its upper part (Fig. 208) and sandstones and shales in its lower portion, the former being thrust over the latter by faulting. The rocks are also cut by numerous fracture and joint planes. In the lower beds there is moreover a coal bed which was being mined.

FIG. 209. — View of Turtle Mountain, Frank, Alberta, showing place from which rock fell, and a portion of slide in foreground. (H. Ries, photo.)

When the great mass of rock estimated at 40,000,000 cubic yards broke loose it was dashed to the base of the mountain, plowed its way across the valley and 400 feet up the other side. The slide material covered 1.03 square miles in the valley to a depth of from 5 to 150 feet.

The slide or rather rock fall was due to a combination of causes, as follows: (1) The form and structure of Turtle Mountain, which had a steep face, weak base, and was much jointed; (2) earthquake tremors in 1901 which probably loosened the rock somewhat; (3) a period of heavy precipitation and heavy frost; (4) the mining of coal from the seam along the foot of the mountain which removed

some of the support. Curiously enough the width of the slide was about the same as that of the mine workings.

When the rock mass fell from the south peak it buried a number of ranches in the valley and a portion of the town of Frank.

Since this slide occurred a widening crack which appeared on top of the northern peak gave rise to the fear that this might also fall. Accordingly a commission was appointed to investigate the matter, and advised moving the town of Frank farther up the valley, and also discontinuing the mining of coal under the northern peak (Ref. 3).

Rock and clay falls are often caused along valleys by streams undermining their walls, or along the seacoast by waves undercutting the cliffs.

Rock falls do not always descend on to land, but sometimes are precipitated into water, thus initiating waves of greater or less size. These may be destructive to boats, and in the case of small lakes roll up on the surrounding shores destroying buildings and life (Ref. 2).

Engineering Considerations

Knowing that landslides frequently follow excavating operations, it becomes important for the engineer to know if possible what degree of slope is safe in different kinds of rocks.

Before explaining this, it is desirable to understand the meaning of several terms that are sometimes used, such as *angle of rest, angle of slide,* and *excavation deformation.*

Angle of rest. — This is the angle (with a horizontal plane) at which loose material will stand on a horizontal base without sliding. It is often between 30° and 35°.

Angle of slide. — This may be defined as the slope (measured in degrees deviation from horizontality) on which a slide will start. It is perhaps self-evident that it may vary considerably, depending on several factors, such as: (1) The weight of the overlying mass above the slipping plane; (2) the character of the slipping surface, whether flat or undulating, and whether dry or wet. Clay, when wet, makes a very slippery surface; (3) character of material below slipping surface, and whether it will flow under pressure, like a wet clay. If this under clay squeezes out, a slide may be initiated on a slope of very low inclination.

As illustrative of the second point, mention may be made of an occurrence along the West Shore Railroad south of Newburgh, N. Y. Here considerable broken stone was dumped along the river bank to make a fill for the road. Although the slope of the mass did not exceed the angle of repose, there was much sliding. It was finally discovered

that the river bottom on which the rock was dumped consisted of hard mud with a 20-degree slope, running down to 300 feet depth, and formed a splendid slipping surface.

Excavation deformation.[1] — It has been suggested that the special name of *excavation deformation* should be applied to the zone around any excavation within which a structure might be disturbed by rock movements resulting from that excavation.

Factors affecting excavation deformations. — The strains set up in the rocks adjoining an excavation may be due to: (1) Natural processes, as stream erosion, solution, fault escarpments, etc.; and (2) artificial causes, as open cuts, underground and submarine excavations. The extent to which any of these affect the rock is said to depend on:

(1) Crushing and tensile strength of large masses of the material involved; (2) physical and chemical character of the rock units; (3) amount and character of groundwater; (4) earth tremors set up by earthquakes, blasts, trains, etc.; and (5) other factors, as: (*a*) heavy structures next to excavations; (*b*) water freezing in rock openings, and wedging off rock masses; (*c*) variations of barometric pressure; and (*d*) earth strains from kneading or tidal pull.

These factors may be briefly discussed:

1 and 2. A rock of high crushing strength, with few joint or other planes, will stand with a face that is practically vertical. The same rock, much cut by fracture planes, sloughs off masses from steep slopes, until a certain angle of permanent slope is attained. Any fissures inclining towards the excavation tend to cause slides, especially bedding planes with shale, lignite or other greasy rock surfaces, or fault planes, with talcose partings. Such slides may occur even if the planes slope but gently, and have relatively slight back pressure.

With rock of low crushing strength, but relatively high tensile strength, slide movement shows sinking near excavations, slight advance of lower slope towards cut, and bulging upward of the excavation floor.

3. Very soft rocks, such as fine-grained and compact argillites and clays, may maintain a vertical face until excavation reaches a depth of 45 to 120 feet, or until unbalanced pressure is great enough to cause them to deform. Such deformation destroys stability of the clayey cementing materials, loosens them up so that surface water can enter, and causes mobility of the mass, with the result that the slope may break back from almost perpendicular to 1 on 10.

Deformations of the above type have occurred in the volcanic clay rocks of the Culebra cut of the Panama Canal.

Excavations which change the water table level may weaken surrounding rocks by dissolving and loosening their more soluble parts, especially in regions where the groundwater contains much carbon dioxide and organic acids.

4. Groundwater in rocks exerts a weakening influence, increasing their tendency to deformation because: (1) It adds to weight of the rock mass; (2) weakens the rock by solution and softening; and (3) increases the mobility of a mass of rock material.

[1] Freely abstracted from Ref. 5.

If a porous rock rests on an impervious one, the water descending through the former will not only be deflected by the latter, but the wet clay particles carried down to this contact surface facilitate slipping. Even capillary water in a weak rock is a source of danger, for with deformation much of the capillary water may be crushed into the larger shear planes, thus giving them increased lubrication. In estimating sliding or deforming tendencies of a rock, careful determinations of its water content should be made on both fresh and air-dried samples.

The most troublesome slides of Culebra cut occurred in fine-grained basic volcanic clay shales of fairly massive character, which show from 6 to 17 per cent of water.

5. Earthquakes may be a cause of deforming movements in rock masses, but blasting is a common cause. Surface blasts cause less subsurface vibration than deep ones. Two large blasts in Culebra cut gave the following approximate vibration records. A blast of 2250 pounds of dynamite, exploded in 14-, 24-, and 28-foot holes, gave a maximum amplitude of vibration of 20 mm. at 1100 feet distance. Another of 5370 pounds of dynamite exploded in forty-eight 24-foot holes at about the same distance gave an amplitude of 28 mm. vibration on the recording instrument. But as the magnification of the latter was 10, the earthwaves set up by the blasts were about 2 and 2.88 mm. respectively, or enough to damage seriously a steep slope of brittle rocks already heavily strained. Railway trains may also set up sufficient vibration to cause damage.

6. Heavy structures near excavations increase a tendency to slide, as subway and foundation engineers know. Variations in barometric pressure and the kneading of tidal pull are not to be overlooked. The maximum variations in atmospheric pressure near sea level may be over 4,000,000 tons per square mile.

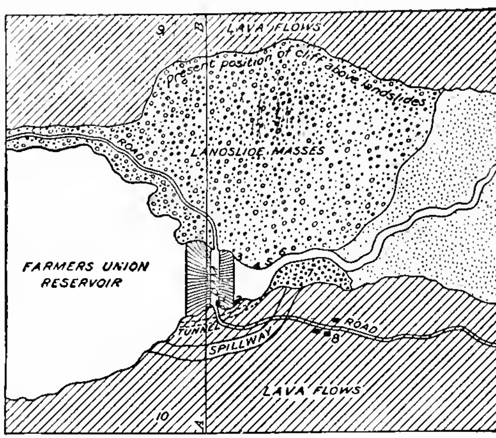

Fig. 210. — Map showing reservoir held in partly by landslide material, near Creede, Colo. (After Atwood, U. S. Geol. Surv., Bull. 685.)

Landslides and reservoir sites. — Valleys are sometimes locally restricted by débris from landslides, and such locations are often selected because of their topographic character as desirable sites for dams. But while the topographic conditions may be satisfactory the landslide masses are not always able to withstand the pressure of a high head of water without serious leakage.

Such landslide deposits because of the abundance of angular rock fragments which they contain may often be more or less permeable in character. They may occur on one or both sides of a valley, sometimes meeting in the center.

Landslide masses may be distinguished from glacial deposits (which sometimes occur in the same region) by the following criteria. The materials composing them are angular, and the individual stones are not polished or striated. They do not contain as large a variety of rocks as the glacial deposits, the materials come from formations in the cliffs above them, and they are often of smaller extent. Moreover they show a close association with the cliffs from which they have been derived. They resemble glacial deposits in showing no assortment of material, and both may show depressions which are sometimes occupied by lakes.

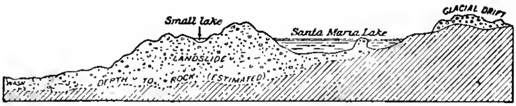

Fig. 211. — Section along line *AB* of Fig. 210.

The Farmers Union Reservoir, thirty-three miles from Creede, Colo., is held in by a dam about 100 feet high and 400 feet wide (Figs. 210 and 211) constructed against a landslide. There has been seepage through the landslide mass, as well as through the much-fractured bed rock at one place. At one point the water had evidently passed through one-eighth to one-quarter mile of slide material. If enough clay seeps in with the water the pores may get clogged; on the other hand there is danger that the waters may flow through in such volume and with such velocity as to wash the finer materials out of the landslide mass and render it even more permeable (Ref. 1).

Land Subsidence

The removal of large volumes of rock underground often causes a settling of the overlying rocks, which may extend to the surface (Refs. 7, 8). Such subsidence may be due to the removal of soluble materials like salt or limestone, by underground waters, but in most cases is due to mining, the chief trouble being caused by coal mining, which frequently extends over large areas.

The question of support and stability of the surface is a serious one, as it affects municipalities, railroads, agriculture, etc. Indeed many cases of subsidence are on record, especially in European localities.

The damage to municipalities caused by subsidence includes that done to streets, sidewalks, sewers, pipe lines, and foundations.

Where transportation is affected it involves damage to railroads, canals, and bridges, the sinking of the land being sometimes gradual, which requires filling as the settling proceeds. In some cases, for example, canals have been maintained at grade while the land settled 20 feet.

Agriculture may be affected by uneven settling of the surface which disarranges the surface drainage and causes ponds to form. It is

said that Illinois drainage projects to remedy the trouble have cost from $15 to $40 per acre.

The geologic conditions affecting subsidence include: (1) General character and dip of strata; (2) presence of faults, fissures, and other fractures; (3) direction of workings with regard to jointing of strata; (4) compressive strength of rocks forming the overlying beds; (5) bearing power of underlying beds; and (6) angles at which rocks break when stressed.

Large workings near the surface cause subsidence unless the proper precautions are taken, but the depth below surface where workings may be excavated without causing trouble above, ranges in different observed cases from 50 to 2400 feet.

At Sutherland, England, where the beds are 50 per cent hard rock, coal beds 1400 to 1800 feet deep have been worked for 70 years without surface disturbance, while in Midland and South Yorkshire, where the rock is largely soft shales, workings at a depth of 2000 feet affect the surface. Much damage by subsidence has been caused in the city of Scranton, Pa.

A steeply inclined excavation is less liable to cause an extended subsidence than a flatter one, but in both cases of course the number, size, and position of pillars supporting the roof of the mine workings is a factor.

Hard brittle rock when broken increases in volume more than plastic rock which tends to pack together, hence the former fills up the cavity faster, and subsidence upward is retarded. Soft rocks on the other hand sink more slowly and more regularly.

Where the rock is cut by extensive fractures, these may bound the subsiding area so that it settles like a block between them. If then we are dealing with a tilted bed, cut by joints at right angles to it, the subsidence of surface may not be exactly over the area of the mine in which the roof settles. Furthermore if the bed rock is covered by unconsolidated material, the subsidence may spread out in this over a wider area than the settled portion of the bed rock occupies. This then results sometimes in the movement at the surface being horizontal as well as vertical.

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CHAPTER VIII

RELATION OF WAVE ACTION AND SHORE CURRENTS TO COASTS AND HARBORS

Introductory. — Commercial intercourse between nations having coast lines, coastwise traffic on the ocean or inland bodies of water, etc., demand the existence and maintenance of good harbors, as well as the preservation of shore lines. Along some coasts excellent natural harbors exist while along others some of the harbors, at least, require improvement by engineers. In either case the harbor is sometimes closed up or shallowed, either by sedimentation or gradual uplift or both, if natural forces are allowed to operate undisturbed.

There are cases, of course, where a harbor may become improved without the work of man. Thus, subsidence of the land, accompanied by little or no sedimentation, or in excess of sedimentation, will result in the deepening of harbors along coast lines of rugged topography.

The harbors of the middle and south Atlantic coast of the United States are noteworthy examples of those which are difficult to keep open and navigable, because the sandy materials forming the coast are being continually shifted by waves and currents.

The trouble is caused primarily by wind and waves acting together in breaking down the shore line,[1] while currents the indirect results of these agencies transport the products of attack from one part of the coast to another, but the shore topography and the sediment brought by the streams from the land are also factors that enter into the problem. In addition to this the effect of tides in places also produces results that are not to be overlooked.

The engineer who is engaged in harbor improvements or maintenance should familiarize himself with the manner in which these agents work, so that he can if possible counteract or prepare for their operations, or even utilize their power to aid him.

Formation of Waves

Cause of waves. — The most common waves are generated by the wind.[2] When a strong wind blows across the surface of the ocean or

[1] The phenomena of wave action and shore currents are not confined to the ocean, but have full play on lakes and inland seas as well, where the water can be agitated sufficiently by the wind.

[2] Destructive waves of great size are sometimes produced by earthquake movements and submarine volcanic eruptions.

lake, it starts each particle of water near the surface oscillating in an orbit which is approximately circular and lies in a vertical plane. In the case of an off-shore wave there is probably little advance of the water, so that each particle returns nearly to its starting point.

In waves known as the swell, which is outside the area directly affected by the wind,[1] the particles have closed orbits, so that there is no permanent advance of the water. But in the wind wave, the particle advances slightly more than it recedes, each particle describing an ellipse rather than a circle, which develops a current that is slower than the wind.

If we think of the water as being made up of layers, then the top layer will move a little faster than the one next below and so on.

Waves developed in open water are known as *oscillatory* waves. The revolution of the water particles in their orbits can be told by watching a floating object, which moves up and down as the waves pass it, but shows very little forward movement.

Zone of breakers. — As a wave approaches a shelving shore, its form changes, and the wave becomes both higher and shorter, the crest becomes steeper and sharper with the velocity of the advancing particle of water increased, and the front steeper than the back. This results finally in the breaking of the wave.

Waves of a given height will break in the same depth of water, and the line of *breakers* is that along which the incoming waves collapse.

The waves developed in shallow water, when the oscillatory waves break, are known as *waves of translation.* In these there is an actual forward movement of the water mass which follows no definite law.

These waves are quite efficient in sweeping material ashore during their forward dash. The return wash down the beach meets the next incoming translatory wave.

There is usually a zone between the water's edge and the breaker line, where material is being washed back and forth.

Waves break when the depth of water reckoned from undisturbed sea level is equal to the height of the crest above the trough. Thus for example if a wave 8 or 9 feet high (or about 6 feet above still water level) is noticed breaking over a submarine bar, it indicates that the mean depth of the water is only about 8 or 9 feet, or 6 feet below the trough. This is not a fast rule, for it may be affected by such factors as the undertow (p. 266) or by a submarine terrace deflecting the water upward.

[1] The appearance of the swell sometimes indicates the approach of a gale several hours in advance of its arrival.

Depth of wind disturbance. — Wave disturbance does not extend to great depths because the size of the orbits decreases rapidly with depth. Thus at one wave length below the surface the water particles are moving in orbits whose diameters are $\frac{1}{534.5}$ those on the surface. Or, in the case of a wave 20 feet high and 400 feet long, the orbit at the depth of 400 feet would be $\frac{4}{10}$ inch. This fact is of interest to engineers, because of its relation to the disturbance of submarine structures. Engineering operations have shown that submarine structures are little disturbed at depths of five meters in the Mediterranean, and eight meters in the Atlantic Ocean.

Débris as coarse as gravel, which is transported by rolling on the bottom, is not infrequently carried out to depths of 50 and sometimes even to 150 feet. Fine sediment, like silt, is disturbed at still greater depths, for ripple marks which are usually present in the finest sediments, and indicate agitation of the water, are said to have been found at depths of 100 fathoms.

Wave dimensions. — Waves vary greatly in size, but those produced by storm winds on the open ocean may be of large dimensions. The *length* of a wave is the distance from crest to crest, while the *height* is the vertical distance between bottom of trough and top of crest. According to Johnson (Ref. 5) the height of oscillatory waves depends on: (1) Strength of wind; (2) duration of wind; and (3) area of surface. Thus: Velocity of wind (miles per hour) $\div$ 2.05 = height of waves in feet. The following figures of wave heights as measured at certain times are given.

	Feet
Lake Superior	20–25
Mediterranean	25–30
Southern Ocean	40–50

The ratio between length and height is given as follows:

Wave length	Height		Length
Under 100 ft.	1	:	17
100–200	1	:	20
300–400	1	:	27

Storm waves in the Atlantic rarely exceed 600–700 feet. Johnson states that the greatest trustworthy measurement of wave length recorded is one from the north Atlantic measuring 2750 feet.

Velocity of waves. — The velocity of an oscillatory wave depends on its length and is proportional to the square root of the wave length. Large ones may advance at a rate of over 30 miles per hour.

The velocity in miles per hour $= \sqrt{2\frac{1}{4} \times \text{wave length in feet}}$.

The velocity in feet per second $= 2\frac{1}{4} \sqrt{\text{wave length in feet}}$.

Shallow water waves advance less rapidly than deep water ones and

they obey different laws, the calculation of their speed being less simple (Ref. 5).

Wave pressure. — The pressure exerted by waves may be *dynamic* or that of the moving water, or it may be *static* or due to the weight of the water. The latter is the lesser of the two.

The damage done to coast lines and to harbors is most impressive evidence of wave pressure.

The following figures quoted from Johnson (Ref. 5) will serve as illustrations.

On Lake Superior, Gaillard determined the static pressure of a wave 10.5 feet high and 150 feet long to be about 450 pounds per square foot, the dynamometer being 9 feet below the wave crest. The dynamic pressures of waves 10 feet high and 150 feet long varied from 460 to 965 pounds per square foot as determined by a dynamometer placed a foot higher than that used for determining the static pressure.

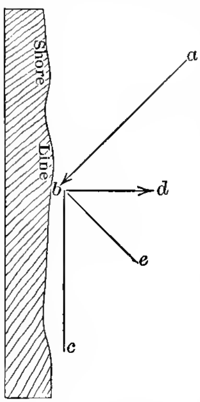


FIG. 212. — Diagram showing relative directions of wave (*ab*), undertow (*bd*), and shore current (*bc*). Particle carried in by wave in direction *ab*, but by undertow and shore current action on it, in direction *be*. (After Chamberlin and Salisbury, Geology, I.)

Storm waves on Lake Superior develop a blow of 1600 to 2500 pounds per square foot, while those on the Scotch coast in winter average 2086 pounds per square foot with a maximum of 6083 pounds.

More impressive perhaps are the following examples:

At Cherbourg, France, a stone of 7000 lbs. was thrown over a 20-foot wall.

At Wick Harbor in 1872 the seaward end of a breakwater was protected by a monolithic block of cement rubble 45 ft. long, 26 ft. wide, 11 ft. thick and weighing over 800 tons. It rested on blocks of stone bound solidly to the monolith by $3\frac{1}{2}$-in. iron rods. The whole mass weighing 1350 tons was torn away by the waves and dropped inside the pier. It was later replaced by one of 2500 tons and this was also carried away.

Undertow. — The water which is piled up against the shore by the waves is returned by the undertow. This is a permanent outward current normal to the coast line, of pulsating character.

Another function of the undertow is to dispose of material eroded by the waves by conveying it seaward, which helps to scour the submerged shelf across which the waves are eating their way into the land.

If a wave approaches the shore at an angle, there will be a tendency for it to start a *shore current*, and the drift thus set up is a strong factor in the transportation of sediment along shore.

Thus in Fig. 212, the line *ab* represents the direction of the incoming wave, *bd* the direction of undertow, and *bc* direction of shore current. A particle of sediment affected by both shore current and undertow would tend to move in the direction *be*, which represents the resultant of the two forces. But the next incoming wave would move it in the direction *ab* again. It would therefore migrate in the direction *bc*, but follow a zigzag path in doing so.

Work Performed by Waves

The work accomplished by waves in general may be classified under (1) erosion, (2) transportation, and (3) deposition, and in this they are aided by shore currents.

Erosion. — Waves beating against the shore perform erosion, chiefly by the impact of the water and by the débris which the water carries, as well as in other less important ways. The impact of the water alone may cause considerable erosion if the coast line is of weak or unconsolidated material, or if the rock consists of alternating weak and strong material, the removal of the former may leave the latter unsupported and cause it to collapse.

Forcing of the water into joint planes and other similar spaces can produce hydraulic pressure, sufficient to disrupt the rock if it is weak, especially when made so by weathering. Very little effect is accomplished by waves of clear water, on solid, hard and fresh rocks. Storm waves especially strike a blow of tremendous force (p. 266).

The erosive work of waves is greatly augmented by the débris which the waters are able to move. Thus sand, pebbles, and stones moved by the waves, not only serve as weapons of attack against the coast itself, but also help to break down loose rock fragments too large for the waves themselves to move.

These large fragments gradually become worn down by the detritus which is moved back and forth over them, until they are finally small enough for the waves to move back and forth, using them in turn as cutting tools.

The effectiveness of the waves will depend on their strength, and on the concentration of their blows. The former is dependent on: (1) Strength of wind, (2) depth of water, and (3) expanse of water across which the wind can sweep. The latter is dependent on the slope of the surface against which the waves break.

Vertical range of wave action. — The range of wave erosion is as restricted vertically as it is horizontally, but it may be extended somewhat by the rise and fall of the tide. The efficient impact of the wave is limited by the crest above and the bottom of the trough. The

range indirectly, however, is often great, being limited by the height of the shore only, for by the under-mining of a cliff, a considerable mass of material may be brought down. This fallen mass will temporarily protect the shore against wave action, until it is broken up and disposed of. Frost also dislodges more or less rock and soil from the face of sea cliffs.

Recession of coast. — As a result of wave attack, the sea sometimes encroaches on the land, and protection walls are necessary in order to prevent the destruction of buildings, roads, railway tracks, etc.

This recession may be especially rapid on sandy coasts, such as that of New Jersey, and many different forms of walls, bulkheads, and jetties have been constructed by riparian owners with varying results. In some cases failure is due to improper type of protective work, in others it may be due to lack of concerted effort at different points along the shore.

Wave Cut Topography

Cliff and terrace. — Waves cutting into and undermining the shore at the water level develop a *sea cliff*, whose slope will depend on the character of material and rate of cutting, and where height will depend on the height of the land on which the sea advances. The structure of the rocks with respect to joints and bedding planes will also exert an influence on the profile of the cliff.

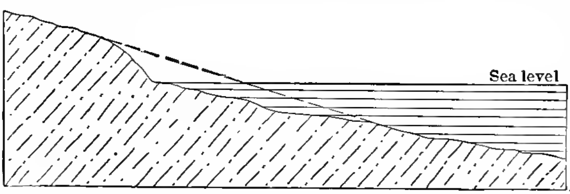


FIG. 213. — Section of wave-cut terrace in gentle slope. (After Gilbert.)

At the base of the sea cliff there is a submerged shelf, covered by shallow water, the *wave-cut terrace*. (Fig. 213.)

In some cases the land has been elevated since the terrace was cut, so that it is now preserved as a bench above sea level, as for example on the coast of southern California.

Terraces formed by wave action against hard rocks are necessarily entirely of wave-cut character, but may have a seaward extension of material carried out by the undertow and dropped on the front slope of the shelf.

Coast outline. — The outline of a coast as developed by wave erosion depends on the character of the rock, its structure, and original outline. The following cases may be cited:

1. A regular coast, equally exposed, but of unequally resistant material, is made more irregular by wave action, resulting in the development of headlands where the rock is hard, and indentations or bays where the materials are soft, or much fractured, so as to be easily eroded. 2. A regular coast, unequally exposed, but of uniform material, becomes more irregular. 3. An irregular coast, of uniform or homogeneous material, becomes more regular.

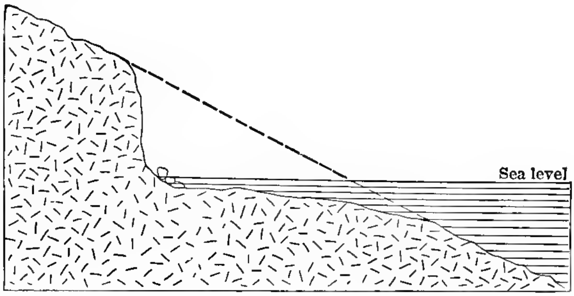


FIG. 214. — Section of wave-cut terrace on steeply sloping coast. (After Gilbert, U. S. Geol. Survey, 5th Ann. Rept.)

Transportation by shore currents. — The incoming waves tend to shift material toward the shore, especially inside the line of breakers, while the undertow tends to carry it out (seaward) again. If the waves strike the shore obliquely, the particles of sediment follow a zigzag path along shore — the direction of littoral or shore current. Coarse materials accumulate where the disturbance of the water is greatest, while finer material is moved even when the water is less agitated.

FIG. 215. — Cliffs formed by wave action, Sydney, C. B. (H. Ries, photo.)

The coarse material covering the bottom, in shallow water along

shore, or where agitation reaches the bottom, is termed the *shore drift.* It may include either material derived by wave action or that delivered to the sea by streams, or both.

Shore Deposition Topography

Beach and barrier. — The *beach* (Fig. 216) is the belt or zone occupied by the moving shore drift, and it may have a variable width. The upper margin is the level reached by storm waves; its lower margin is slightly beyond the breaker line of storm waves. While the beach follows the water and land boundary in a general way, it does not conform to all the minor irregularities, such as indentations and projections.

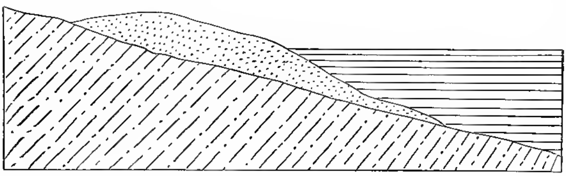


Fig. 216. — Section of a beach ridge. (After Gilbert.)

If the slope of the coast is flat, then the undertow is weaker than the shoreward movement of the waves, and the material is shifted shoreward, being cast up near the water's edge and forming a beach ridge (Fig. 216).

If the sea or lake bottom near shore has a very gentle slope, the waves break some distance out from the shore line. It is at this point of greatest agitation that deposition takes place, and a ridge may be built up known as a *barrier beach* (Fig. 217). If now the storm waves build this up above the water surface, a lagoon is formed between the barrier and the mainland, which may eventually become filled by sediment (Fig. 219). The lagoon at one stage of

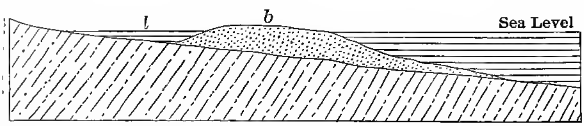


Fig. 217. — Section of a barrier beach; *b*, barrier; *l*, lagoon. (After Gilbert.)

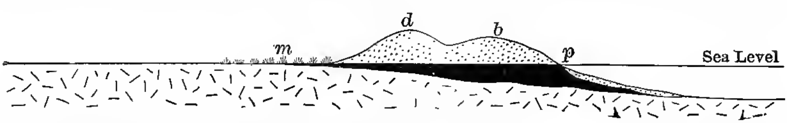


Fig. 218. — Section of a barrier beach which has moved inland, part way across a marshy lagoon. *b*, barrier; *m*, marsh; *p*, peat; *d*, dune. (After Goldthwait, Ill. Geol. Survey, Bull. 7, 1908.)

filling becomes a marsh. Most of the material is washed in from the land, but some may be brought in by tidal currents.

Barrier beaches are not only liable to shift (Fig. 218), but are sometimes of considerable width. At Atlantic City (Fig. 219), on the coast

FIG. 219. — Map showing barrier beach and partly filled lagoon behind. (After Kümmel, N. J. Geol. Survey, Rept., 1907.)

of New Jersey, a barrier one mile broad has formed and at present is growing on the seaward side, although formerly it was eroded at different periods.

The sand which is piled high on either a beach or barrier is not allowed to rest, but is carried by the wind and heaped up to form sand dunes (Chapter II). An artificial barrier will sometimes cause a dune 10 feet high to build up in one season.

Spits, hooks, and bars. — The littoral or shore current does not follow the larger indentations of the coast. In maintaining its course across the mouth of a bay, the current may pass into deeper water. This results in checking the velocity of the current, and the deposition of a part at least of the sediment it is carrying.

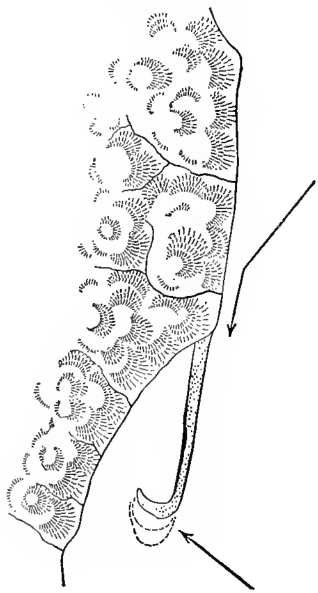


FIG. 220. — Sketch map showing the development of a hooked spit. (After Goldthwait, Ill. Geol. Survey, Bull. 7, 1908.)

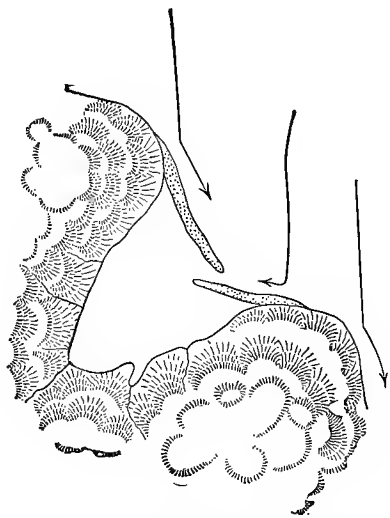


FIG. 221. — Sketch map showing a bay enclosed by a pair of overlapping spits. The arrows indicate the direction of the wind-driven currents. (After Goldthwait, Ill. Geol. Survey, Bull. 7, 1908.)

The deposited material assumes the form of a submerged ridge, usually narrow, across the mouth of the bay, and is termed a *spit* (Figs. 220 and 222), so long as it is free. As the level of the ridge is built up towards the water surface, it comes within the zone of agitation of the waves, and by these it may be built up above the surface of the water. Spits are also at times built out from projecting spurs of the coast line.

A strong current, even of temporary character, flowing past the end

FIG. 222. — Hooked spit of sand, mouth of Ausable River, Lake Champlain, N. Y. (H. Ries, photo.)

of the spit, may cause it to curve into a *hook* (Figs. 220 and 222), and this will occasionally change its position because of change in the direction of the wind.

FIG. 223. — Beach and sand dunes formed by wave and wind across harbor of Inverness, N. S. (H. Ries, photo.)

If the spit completely crosses a bay and becomes tied to the opposite shore it is called a *bar*, and many lakes have been formed by the upbuilding of a bar across the mouth of a bay. Bars sometimes tie islands to the mainland.

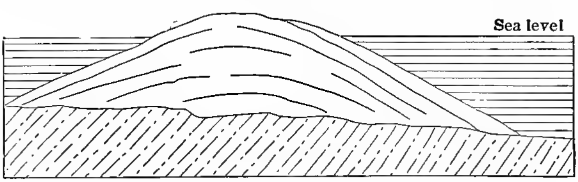


FIG. 224. — Section of a bar. (After Gilbert.)

Conditions are frequently quite different where an active stream enters the bay, for then the outflow from the bay may be strong enough to prevent the completion of the bar.

At other times the growth of the raised spit across a bay may gradually shift the stream channel towards the farther side of the bay, considering the direction of shore drift. If the ridge building still en-

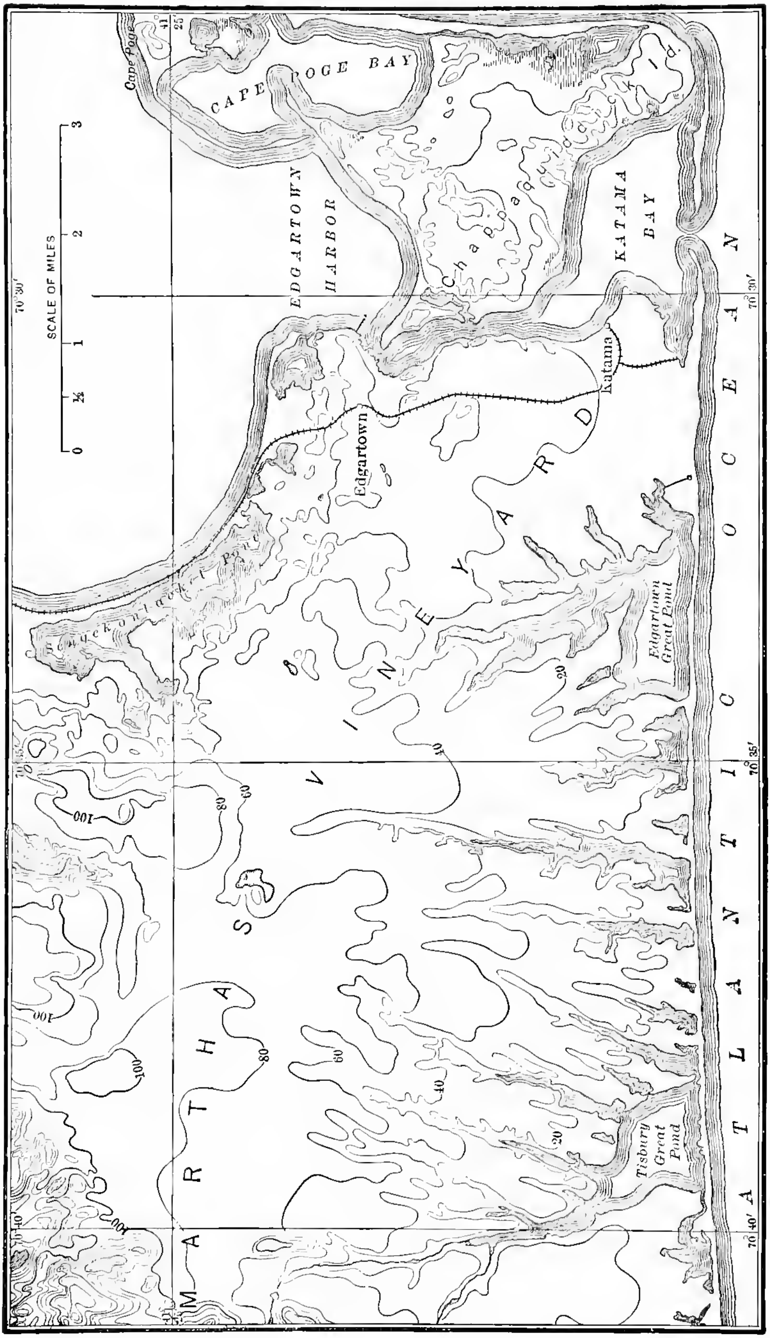


FIG. 225. — Shore line changes at Martha's Vineyard. (U. S. Geol. Surv.)

croaches on the stream channel the latter may break through the spit at another point, but if the stream is completely blocked the water may seep out through the beach gravels.

Figure 223 shows an interesting occurrence at Inverness, Nova Scotia. Here the small harbor which was to have been used for shipping coal from the neighboring mines became completely closed by a bar of shore drift from the north. The stream flow was too weak to keep a channel way open across the bar, and dredging was equally ineffective. Jetties which were constructed became buried in the drifting sand. In addition the wind picked up the sand from the upper edge of the beach and piled it into dunes.

Tidal scour is another factor tending to maintain a channel way (*thorofare*) across a spit or barrier beach. Sediment brought in by the tidal current is sometimes deposited inside the entrance forming a shoal, which is obstructive to navigation.

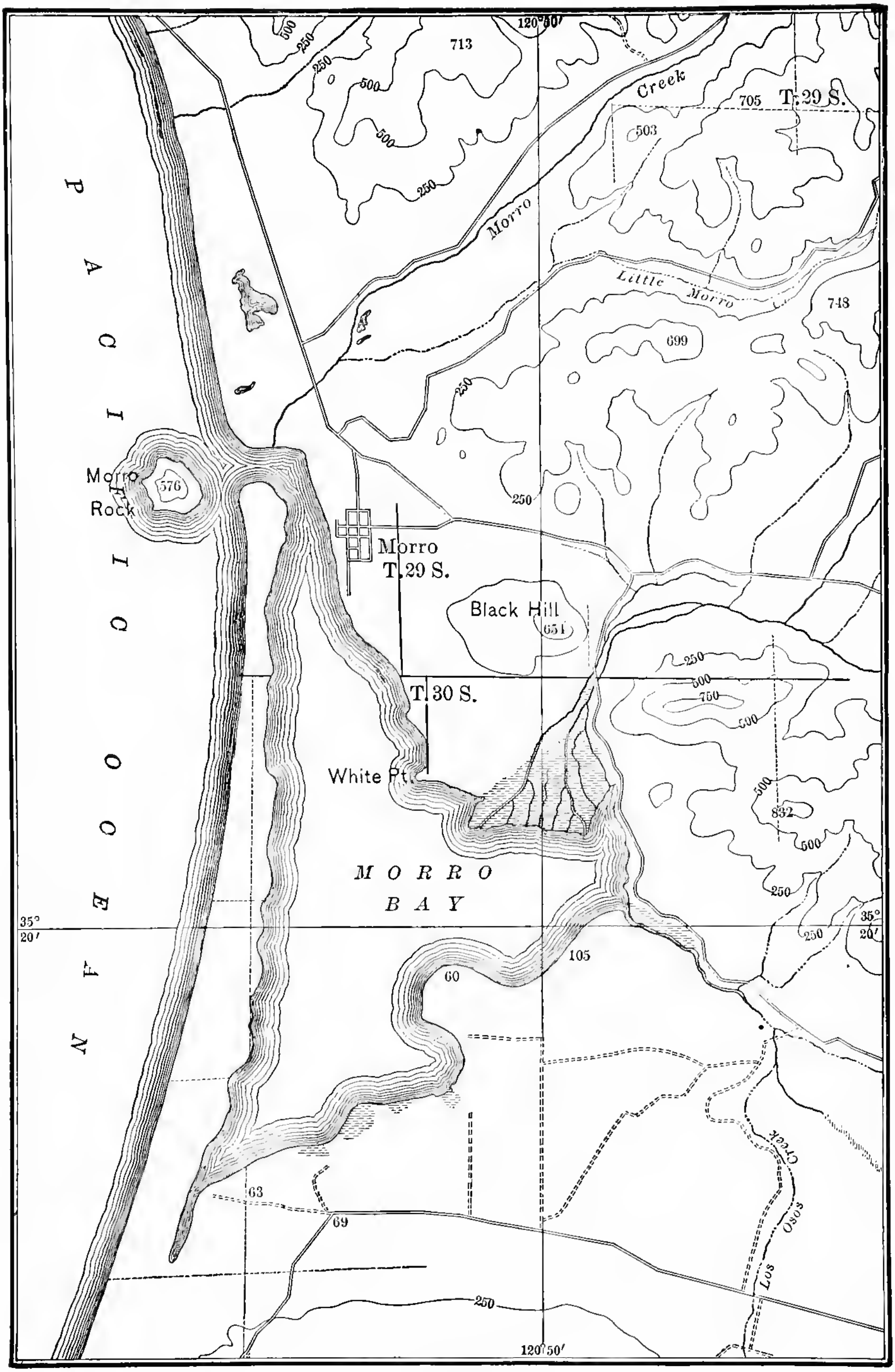
Although shore drift may move in opposite directions at different times, there is usually a positive resultant in one direction, the determination of which is of importance in bar improvement.

The tidal wave can produce a current which is separate from the littoral (shore) current.

Examples of changes in shore line. — Figures 225, 226 and 227 illustrate well the changes that may take place along coast lines by wave and current action.

Figure 225 shows simplification of shore line by deposition (and subordinately by erosion), where the coastal bars deposited by waves and shore currents have closed in a series of bays, converting them into ponds. Little water enters these ponds, but what does, finds its way into the sea by seepage through the sand and gravel of the beach. The only permanent stream is that entering Tisbury Great Pond, and the inflowing water seems to be sufficient here to keep an outlet across the beach. Bars or beaches seem to be in process of development south of Katama Bay, and may in time connect with each other unless the tidal flow between Edgartown Harbor and Katama Bay is sufficiently strong to keep the passage open. The material for building the bars was probably cut from points of land which formerly projected into the water.

Figure 226 represents a shore line where both erosion and deposition are going on. Material eroded by wave action from the cliffs along shore to the south is carried northward by the shore currents and has been deposited to form a bar across Morro Bay. The beach formed on this bar by wave action has been piled up still higher by the wind to form sand dunes. At the head of Morro Bay a delta is



SCALE OF MILES
0 ½ 1 2

FIG. 226. — Shore line changes at Morro Bay, Calif. (U. S. Geol. Surv.)

being built and is gradually encroaching on the water of the bay. Morro rock is an island presumably isolated from the mainland by subsidence, by wave erosion, or by both. The drainage entering the bay prevents the completion of the bar.

Figure 227 shows the development of coastal irregularities by processes which will ultimately result in coast simplification. Material eroded from the coast by wave action to south of limit of map is carried northward by shore currents. The beach built with this sediment terminates in Sandy Hook at the entrance to New York harbor. The hook turns westward because of strong wind, waves and tidal action from the east. At the northwest end of the shore line the coast line is being built out by sedimentation. This part of the coast is protected from strong wave action by Sandy Hook. The north border of Highlands of Navesink is marked by cliffs, formed by wave erosion prior to the existence of Sandy Hook. The bays marked as Navesink River and Shrewsbury River are probably the result of subsidence which has drowned the lower ends of these rivers. The building of the bar across their mouths is another illustration of the process of coast simplification.

Work of tides. — While the work of the tides is of much less importance than that of the waves, it is not by any means to be overlooked.

The tide is a great wave produced by the attraction of the Sun and Moon, which passes around the earth once every 24 hours, but since two waves are formed on opposite sides of the earth a tidal wave passes any given point about every 12 hours.

On the open sea this wave is not noticeable, but when it reaches the coast line of the continents the water is raised up giving *high tide*, then as the wave passes on, the water level falls giving *low tide* conditions.

The work of the tide is especially noticeable where the water flows through narrow openings in barrier beaches, between islands, or enters some bay which narrows towards its head. In the latter case, of which the Bay of Fundy is a good example, the tide advances up the bay as a great wave known as the *bore,* and causes a tidal rise in places of from 40 to 60 feet.

Tidal currents show a varying velocity of from 1 to 12 miles per hour, and where they are flowing through narrow passes it can be seen that they may not only cause trouble to navigation, but will if the channel way is of unconsolidated material also cause considerable scouring. The material thus removed by erosion may be deposited locally as at the head of bays, in lagoons behind barrier beaches, or in harbors.

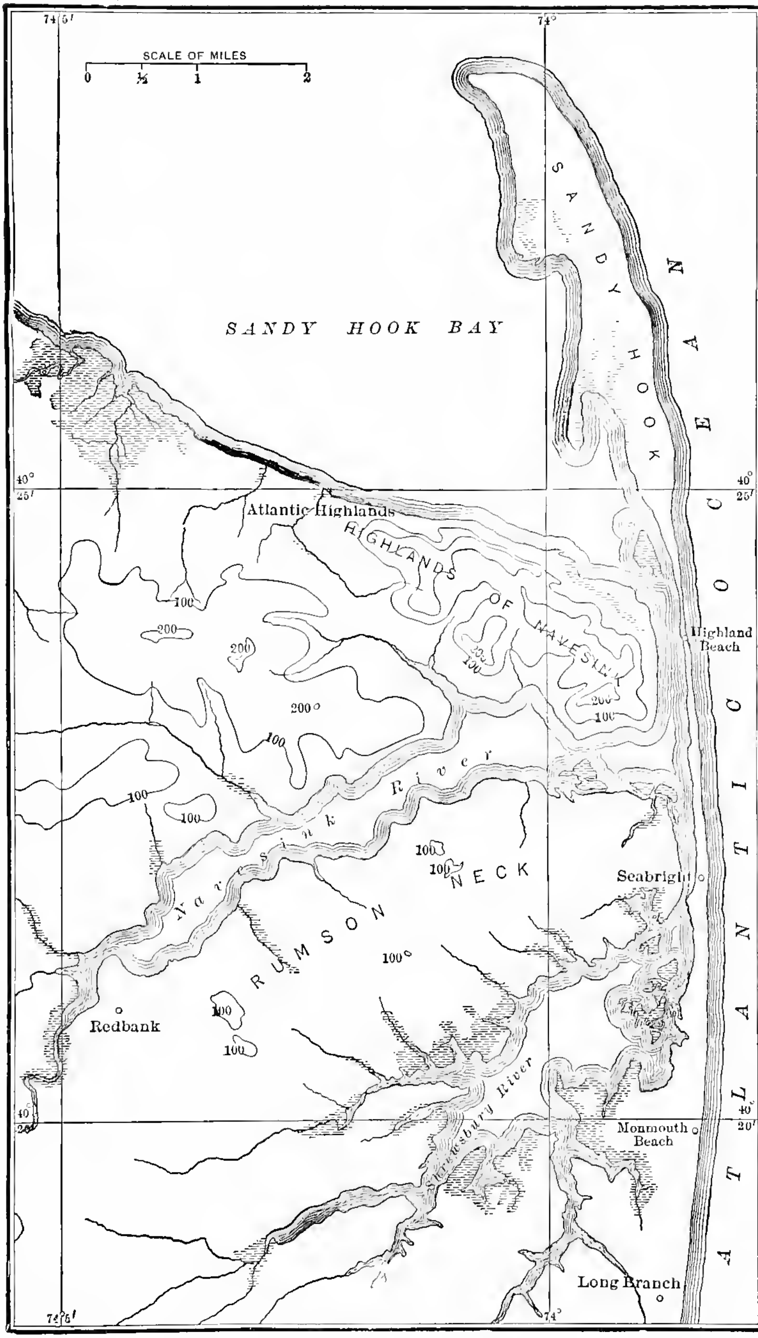


FIG. 227. — Shore line changes at Sandy Hook, N. Y. (U. S. Geol. Surv.)

It is stated that Boston harbor has been filled to a depth of 25 feet with tidal silts, and much red silt has been deposited at the head of the Bay of Fundy.

Problems of Harbor and River Mouth Improvement

Relation of wave and shore current work to harbors. — From what has been said on the preceding pages the engineer will readily observe that harbors can be closed or silted up, or bars formed which shallow the channel, and hence in many cases preventive measures are necessary to combat the work of wind and waves. The formation of these features of shore and sea-floor topography are not the only things that have to be considered.

Equally important to recognize is the fact that many of them are of very temporary character. Spits and bars shift at times with remarkable rapidity as a result of storms (Fig. 228). One storm may close up a thorofare at one point and open up a new one some distance away.

The coast of New Jersey affords some excellent examples of the above,[1] and that portion from Sandy Hook to Cape May is of great importance in many respects, for it forms the southern approach to New York Harbor, and the large tonnage between New York and all southern ports passes close at hand. Although from Sandy Hook to Delaware Breakwater is only 134 miles, more disasters have occurred on this coast than on any other of equal extent in the United States.

This danger is increased by the fact that there are no harbors of refuge along the coast, and the channels at the various inlets are shallow, tortuous, and shifting. The presence of well-defined and fixed channels at several inlets along the coast would go far towards eliminating these dangers.

It is difficult to appreciate what great changes may be wrought upon the beaches during even a single storm, by the action of waves and currents or by the slow deposition at one locality and equally slow wasting at another. The channels of the inlets are constantly changing in depth and location through certain cycles and the inlets themselves are slowly shifting in position. (See Fig. 228.)

Relation of bars to rivers. — Bars[2] are found at the mouths of many rivers, and may be built up in part of river sediment and in part of sediment brought in by waves and tidal currents.

If a sediment-laden river, like the Mississippi, Nile, or Amazon,

[1] N. J. Geol. Survey, Ann. Rept., 1905.

[2] For detailed discussion of this subject see Thomas and Watt, Improvement of Rivers, 2nd ed., part 1, p. 309, 1913. (Wiley and Sons, Inc.)

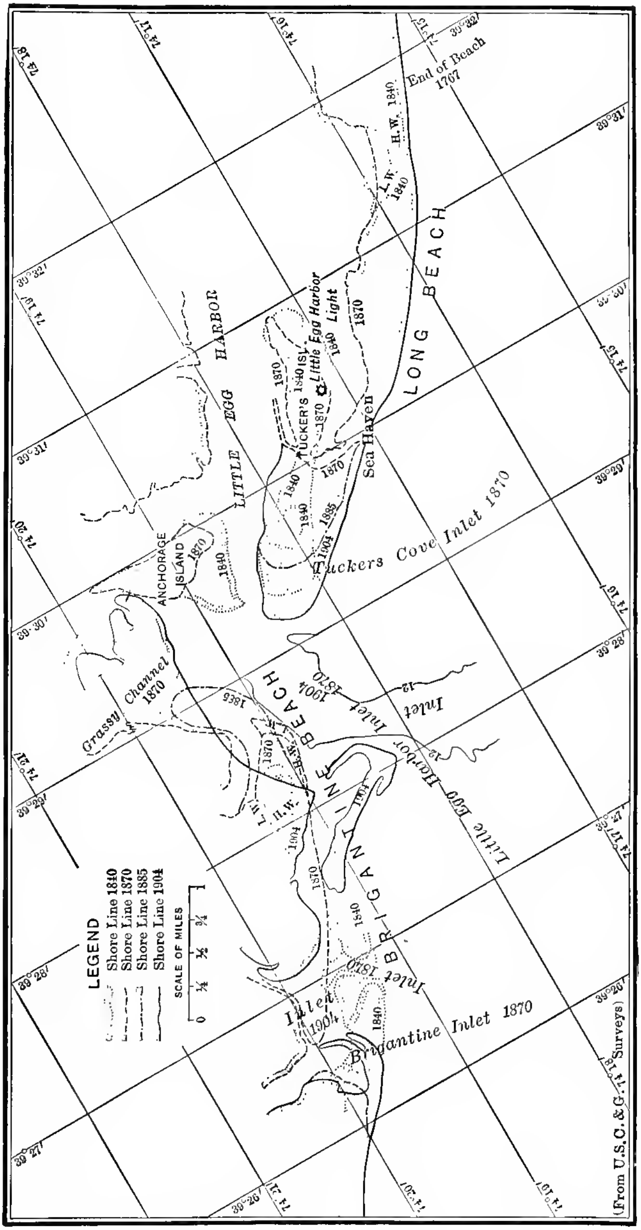


FIG. 228. — Map showing changes in the shore line between Brigantine and Little Egg Harbor Inlets, N. J., between 1840 and 1904. (After Haupt, N. J. Geol. Survey, Rept., 1905.)

enters directly into the sea or lake, checking the velocity of the current, as it meets still water, will cause it to drop its load of sediment, thus forming a bar.

On the other hand, bars at the outlets of lagoons or bays which empty into tidal seas, and which receive the flow of a river, are caused chiefly by the action of the winds and waves, which drive material into and across the mouth. The tidal currents, however, keep the mouth from being closed. In such cases, little actual river silt probably reaches the bar.

In the case of rivers which discharge through a tidal estuary, the bar may be due to conflict of ebb and flood currents at the outfall, which cause eddies and still water; or to the difference in duration of their scouring action; or to waves and sand drift along the shore.

"The operation of the laws [1] governing the formation and the improvement of the outlets of rivers and tidal harbors is usually complex and difficult of any close analysis. The forces at work are generally many and varied, and while the effect of a single one upon a plan for improvement might be foretold, their action in combination can only be approximated.

"There are, for example, as just mentioned, the transportation and deposit of sediment, present in most rivers; the effect of floods and tides; the presence or absence of currents along the coast; and the gradual effects of storms and the drift of shore material, which with small rivers may change the outlet entirely, as with the Yare River on the east coast of England, where the outlet was driven south 4 miles in the course of years, and at Aransas Pass in America, which has moved to the southwest about a mile in the past 50 years. In some cases such causes produce daily changes in the channel, as with the Hoogly, where ships can navigate only in daytime and by constantly taking soundings."

However, close study of the charts of different periods may indicate the existence of certain persistent forces at work, a knowledge and recognition of which will enable the engineer to attack the problem more intelligently.

Rivers which enter tidal estuaries have to be treated differently from those which have non-tidal outlets, without shore currents, or where these currents are slight.

Improvement of tidal rivers. — The principles involved include: (1) Admission of tidal flow freely and as far up the river as possible, in order to reduce the period of slack water to a minimum; (2) maintenance of fresh water discharge as large as possible; (3) preservation of estuary form as regular as possible, with gradual en-

[1] Thomas and Watt, l.c., p. 310.

largement towards sea, and thus promote regularity of flow without restricting tidal capacity of outlet.[1]

Shore drift. — "In deep water, breaking waves and currents disturb the bottom but slightly if at all. In shallow water, however, the waves and currents will stir up and transport the material. Tests made at Cumberland Sound showed that coarse sand and shell, when stirred up by breakers, were carried to a considerable distance even by light currents, and were not deposited till smooth water was reached. The same materials in quiet water lay undisturbed by currents flowing as swiftly as 4 feet per second, although fine sand was found to be moved by comparatively slight currents. This action on exposed coasts leads to a constant movement of the sand or shingle, and if the storms prevail in one direction, there will be a corresponding littoral drift. Where jetties or breakwaters are built under such circumstances there will result an erosion on the leeward side and a filling on the windward side, and this will continue until the latter is rounded out and the sand can travel past the ends of the jetties and continue its movement along the coast. The construction of breakwaters for the harbor of Madras led to an erosion of the neighboring coast for a distance of several miles to the north, in which whole villages were destroyed, and at the harbor of Ceara in Brazil, a similar erosion took place and continued for about three years, until the littoral drift had silted up the windward side and the entrance, and could pass along as before.[2] At the mouth of the St. John's River in Florida, the beach to the south was similarly eroded."

The four general methods used by engineers to improve navigable conditions at the mouths of rivers are:[3] (1) by lateral canals; (2) by dredging; (3) by jetties and dredging combined; and (4) by jetties only.

Much money has been spent for dredging and the construction of jetties at the mouths of the Columbia River, Oregon, and the Mississippi River.

Conditions along the coasts of the United States. — The engineer engaged in harbor improvement along the United States coast lines has to consider a variety of conditions. Along the coast from Maine to Cape Cod and to New York along the shore of the mainland, the coast is mostly rock bound, and the bays often represent valleys that were modified by glacial erosion when the land stood higher, but have

[1] Thomas & Watt, Improvement of Rivers, Vol. I, p. 310.

[2] Proceedings, Inst. Civ. Engrs., Vol. CLVI.

[3] For excellent discussion of this see Thomas & Watt, Improvement of Rivers, Vol. I, p. 314.

now become partly submerged by subsequent sinking of the coast line. At the mouth of some of these bays there are obstructions which consist of rock ledges or glacial detritus. The tidal rise is moderate at Cape Cod, but increases to the northward. The rock is resistant, and hence changes by wave action are not very noticeable.

Improvement in these harbors consists mainly of dredging and rock removal.

From Cape Cod to New York there are a number of island harbors like those of Nantucket, Vineyard Haven, Block Island, and Long Island, all of which are peculiar, and seem to be due to irregularities in the moraine. The tidal rise is only a few feet, but on account of the great interior sounds to be filled, the tidal currents in some places are quite strong. The material of the coast is all unconsolidated. Storms are severe along this part of the coast, and wave effect on the finer materials is often considerable.

The improvement of the harbors is by dredging and by the construction of works for the contraction and protection of the tidal channels.

The shore of the south Atlantic coast, or that portion extending from New Jersey to Florida, is composed mostly of fine materials, which are easily eroded and afford good conditions for the waves and currents. The sea floor extends seaward from 50 to 100 miles, with a uniform slope of 10 feet to the mile. Tidal rise varies from $2\frac{1}{2}$ to 7 feet at different points.

Wave action on the whole is moderate, especially on the southern part of the coast, but nevertheless, the wind waves do considerable work. The harbors are improved by contraction, and protection work and dredging.

Along the Gulf of Mexico, the coast can be divided into two sections. The eastern part is not much exposed to storms, but the on-shore winds of the western portion are strong and continuous. The materials along both sections are easily eroded, and the tidal rise is about one foot. Methods of improvement are similar to those used along the southern Atlantic coast.

Turning to the Pacific coast we find that the materials of the southern part are easily eroded, that the tidal range is large, but that the wind action is small.

On the northern part of the Pacific coast line, material which can be moved by the waves is abundant, but many rocky headlands make the problem somewhat complex. The wave action is tremendous and there are great ocean currents that may have some effect. Tidal action is also strong.

References on Waves and Shore Currents

1. Chamberlin and Salisbury, Geology, I, p. 330, 2nd ed., 1905. (Holt & Co.) 2. Gilbert, U. S. Geol. Surv., Fifth Ann. Rept., p. 80. (Shore line features.) 3. Harts, U. S. A. Corps of Engrs., Prof. Memoirs, Oct. to Dec., 1911. (Harbor improvement on Pacific Coast.) 4. Haupt, Trans. Amer. Soc. Civ. Engrs., XXIII, p. 123, 1890. (Littoral Movements of the New Jersey Coast.) 5. Johnson, Shore Processes and Shore Line Development, N. Y., 1919. (Wiley and Sons, Inc.) (Extensive bibliography.) 6. Thomas and Watt, Improvement of Rivers, New York, 1913. (Wiley and Sons, Inc.) 7. Wheeler, Tidal Rivers, 1893. (Longmans, Green & Co., New York.)

CHAPTER IX

ORIGIN AND RELATION OF LAKES AND SWAMPS TO ENGINEERING WORK

Lakes

Definition. — A lake may be defined as a body of water occupying a more or less basin-shaped depression in the earth's surface. A small lake is called a pond, and a very large lake is sometimes referred to as an inland sea. These terms are, however, loosely used.

Relation to engineering work. — Engineers in the different branches of their work often have to deal with lakes for the following reasons: (1) Lakes frequently serve as sources of water supply for municipal or steaming purposes, hence their volume, and the chemical composition of the water have to be considered; (2) many navigable lakes of large size show changes of shore lines due to wave action (Fig. 229) and shore currents, and problems of coast protection and harbor maintenance have to be dealt with as along the sea coast; and (3) by a natural process lakes are often converted into swamps, across which railroad lines have to be laid, these tracts frequently giving considerable trouble in road-building and maintenance.

Types of Lakes

The formation of lakes is sometimes complex, and their origin may be due to a number of causes; moreover, even after the lake has been formed it is frequently modified in different ways, especially in depth. In North America there are many lakes of varying size and depth, and the table on the following page contains data regarding some of the more important ones.

Lakes may be classified according to origin, and the following grouping has been suggested by Davis: (1) Original consequent lakes; (2) lakes of normal development; and (3) lakes due to accident.

Original Consequent Lakes

This class includes those lakes which occupy original depressions in a land surface, such as irregularities of the ocean bottom which were preserved when it was lifted above sea-level. The Everglades of Florida occupy such a depression. Other examples of this type are

lakes occupying depressions on the surface of lava flows and which are never large, being surrounded by rock walls; depressions in sand dunes, as on Long Island, N. Y., and depressions in glacial till (p. 308) or modified glacial drift (p. 308). Lakes of the last two types are not uncommon for example in Wisconsin.[1] Lakes in the drift may be fed by streams, or by springs issuing along the sides of the depression which the lake occupies. Their level may coincide in a general way with that of the water table (p. 214) of the surrounding region, a good example being Lake Ronkonkoma on Long Island, N. Y.

TABLE GIVING DEPTH AND AREA OF A NUMBER OF NORTH AMERICAN LAKES

Name.	Average depth, feet.	Maximum sounded depth, feet.	Area, square miles.	Area of watershed, square miles.
Athabasca, Alta.-Sask.	....	....	2,842	....
Cayuga, N. Y.	....	435	66.3	1,571.6
Champlain, N. Y.	....	400	436.7	7,750
Crater, Ore.	....	1975	....	....
Erie	70	204	10,000	22,700
Geneva, Wis.	....	142	8 6	....
George, N. Y.	60?	170	43.6	227
Great Bear Lake, N. W. Ty.	....	....	11,820	....
Great Salt Lake	15 to 18	50	2,000 (variable)	....
Great Slave Lake, N. W. Ty.	....	....	10,719	....
Hopatcong, N. J.	....	....	2,443*	25.4
Huron	210	702	23,200	31,700
Mendota, Wis.	....	84	15.2	....
Michigan	335	870	20,200	37,700
Mono, Cal.	61	152	87	7,000
Oconomowoc, Wis.	....	49 2	819*	....
Okechobee, Fla.	....	....	730†	5,366
Oneida, N. Y.	....	....	78	1,352.5
Ontario	300	738	7,260	21,600
Owens, Cal.	....	....	75	....
Seneca, N. Y.	....	612	67.2	708.1
Superior	475	1008	31,800	51,600
Tahoe, Cal.	....	1645	195	324
Winnipegosis	....	....	2,086	....
Winnipeg	....	70	9,457	....

* Acres. † When surface stands 20 feet above the Gulf.

Lakes of Normal Development

This class includes all lakes which have been formed in connection with the development of river valleys. Several subtypes deserve notice.

Oxbow lakes. — The formation of these (Fig. 160) has been described under Rivers (Chapter V). They are usually shallow, and of little economic importance. Their banks are usually low, and their shores marshy, while the bottom may be covered with treacherous mud.

Beaches across inlets. — The inlet into which a river discharges is to be regarded as the lower extremity of its valley. As explained under Waves and Shore Currents, Chapter VIII, a bar may sometimes form across a bay (Fig. 225), and be gradually built up to a beach, thus

[1] Fenneman, Wis. Geol. Survey, Bull. VIII, 1902.

more or less completely shutting off any open connection between inlet and sea, so that a lake is formed behind the beach. Even if there remains no open channel between the lake and the outer water, the water of the lake may still escape by seepage through the sand of the beach ridge. Such lakes may be marshy along their shores. Lakes of this type are found, for example, along lakes Erie and Ontario, on Long Island, and along the Massachusetts coast (Fig. 225).

FIG. 229. — Gravelly beach formed by wave action, Kootenay Lake, British Columbia. (H. Ries, photo.)

Sink-hole lakes. — The formation of sink holes in limestone formations is explained in Chapter VI. In some cases these become clogged with débris so that the surface water accumulates in the depression and in some instances the extended breaking down of the limestone by subterranean solution may afford a depression of some size. In other cases there may be an outflow through one or more sink holes in the bottom of the lake, but the level is not lowered unless the escape exceeds the supply.

In the case of Lake Miccosukee, Florida, which has an area of about 5000 acres, it was found that when a channel entering from the southwest was discharging about 200 gallons per minute, the lake level was being gradually lowered, but when the same stream was bringing in approximately 7000 gallons per minute the lake was rapidly filling.[1]

[1] Sellards, Fla. Geol. Surv., 3rd Ann. Rept., 1910.

Sink-hole lakes are rarely large, their sides are steep, and they are sometimes deep.

Crustal-movement lakes. — Depressions capable of holding water are sometimes formed, by warping of the rocks of the earth's crust, either to form a new basin, or else lift up the ends of a preëxisting trough.

Lake Timiskaming in Ontario, nearly 70 miles long, for example, is regarded as a case of the latter.[1] The lake is bounded by rocky shores through much of its length, and is supposed to represent a pre-Glacial canyon which, by the down-warping in its middle part, has become flooded. The total amount of down-warp is estimated at as much as 500 feet in the center of a distance of 50 miles.

Lakes appear to be formed sometimes as the result of faulting, as in the case of the Warner Lakes in Oregon. Here large rectangular blocks of the earth's crust have been tilted by faulting, so that corresponding corners of neighboring blocks have been tilted downward to the same degree. Such lakes are roughly triangular in outline, and bounded on two sides by cliffs, along which the water may be deepest, and shoals off towards the third side. Lake Superior, the Dead Sea, and Lakes Nyassa and Tanganyika belong to his group.

Lakes Due to Accident

This class includes those lakes located along lines of drainage which have become dammed by one cause or another. They are of variable size and differ in their degree of permanency, some being only short-lived.

Drift-dam lakes. — These originate where a dam of glacial drift was deposited across the stream's course at some point, which served to impound the river waters. Lake George in New York State is a lake of this type. The valley above the dam may be in part filled with drift. The tightness of the drift dam will depend on whether it is dense till or gravelly and sandy modified drift.

This is probably the most extensive type of glacial lake. Fig. 233 shows a lake that is being held in a valley by a terminal moraine (p. 307).

The bottom of a lake originating in the manner described above, may be the original rock floor of the valley, but is more likely to be formed of the glacial drift which partly fills the pre-Glacial valley.

In some cases a lake may form behind the terminal moraine of an existing glacier, being held in on one side possibly by the ice itself. Small lakes of this sort are not uncommon in regions of existing glaciers.

[1] Pirsson, Amer. Jour. Sci., 4th series, XXX, p. 25, 1910.

Lake Como, in the Bitter Root Valley, Montana, is described as a deep natural lake basin formed by a terminal moraine of fine and coarse gravel, sand, and rock flour. The Twin Lakes, near Leadville, Colo., are said to be located between two great lateral moraines, and held in by a terminal moraine, which consists chiefly of rock flour and is practically impervious to water.[1]

Landslide lakes. — The name of this type explains the manner of origin, for wherever a landslide of more or less water-tight material crosses a valley occupied by a stream, a lake is likely to be formed.

FIG. 230. — Lake formed by barrier of lava, Central France. (H. Ries, photo.)

Lakes of this type are rarely of great extent. The dam that holds them in may occasionally be of considerable width, and contain much stony material, so that it involves time and trouble to cut a drainage channel across it. The landslides causing an obstruction of the stream may either be material dislodged from the valley slopes, or soft unconsolidated material that has been undermined by the stream. The last type is not effective except in the case of small streams and even then the slide may only obstruct the river temporarily.[2]

[1] Schuyler, Reservoirs, pp. 483 and 487, 1908.

[2] See G. M. Dawson, Geol. Soc. Amer., Bull. X, p. 484, 1899.

Schuyler[1] describes "a natural dam on a branch of the Umpqua river in Oregon, over 300 feet high, formed by a landslide from the adjacent sandstone cliff. The base of this dam is not over 3000 to 4000 feet. Floods of several thousand second-feet pass over the top of it every year, and it is practically water-tight, as it holds back a good-sized lake. This is a natural rock-fill dam composed of enormous blocks of stone, whose voids are filled with smaller stone and rock dust ground up in the process of falling." Crystal Lake in Colorado is a lake of the landslide type.

Lava dams. — In some regions of volcanic activity, a lava flow occasionally obstructs a valley, so that the water becomes ponded behind it. No large water bodies of this type are known. Fig. 230 shows such a lake in south central France. Snag Lake in California is also of this type.

FIG. 231. — Crater lake, volcano of Toluca, Mexico. (H. Ries, photo.)

Crater lakes. — The craters of many extinct volcanoes are often more or less filled with water, but so far as known they have never been used for economic purposes. Indeed they are not very abundant. Fig. 231 shows a crater lake in the volcano of Toluca, Mex., 14,000 feet altitude. Crater Lake, Oregon, which has a diameter of about six miles is one of the largest known. In some regions of present volcanic activity, there may be bubbles rising in the lake due to escape of steam or other gas.[2] Crater lakes must perforce have a small drainage basin and can hardly be drawn upon as a source of water supply for any purpose.

Glacial dams. — The advance of a glacier across a river valley may dam the flow sufficiently to form a lake. In regions of alpine glaciers

[1] Schuyler, Reservoirs, p. 483, 1908.
[2] Hovey, Nat. Geog. Mag., 1902.

they are seldom of large size, and are not to be considered except for threatened danger from floods in the event of their sudden release.

In Alaska, however, a region which will attract the engineers' attention to an increasing degree in the future, the effects of living glaciers on drainage obstruction may have to be occasionally reckoned with. Thus, the constriction of Copper River by Child's glacier gave rise to the lake in which Miles glacier terminates. The lake was crossed by a car ferry until the bridges on the Copper River railroad had been completed.[1]

Lake Waters

Waves and Currents

Wave and ice action. — Wherever a lake is of sufficient size to permit waves and shore currents of any importance to develop, and the coast line is composed of soft materials, we find the same erosion and deposition going on as along the ocean coast line. These phenomena are described in Chapter VIII, and need not therefore be repeated here.

A phenomenon seen in some lakes, not observed in the ocean, is the development of *ice ramparts.* In many lakes the water becomes entirely covered by ice during cold weather. If the ice covering has a temperature of say 20° F., and the temperature is lowered to say −10° F., the ice contracts, which results in its either pulling away from the shore, or cracking. If the former the water uncovered at once freezes; if the latter the water filling the cracks does the same.

When the temperature rises again, the ice expands, and either crowds up against the shore or arches up at some other point. Where the shore is gravelly or composed of other soft material, it is sometimes pushed up into ridges. These often differ from beaches or bars in that the material may be entirely unassorted.

Such ice terraces were noted by Buckley, and have since been described by Fenneman for many of the Wisconsin lakes.[2] Where structures occur along the shores of the lake considerable damage may be caused by the ice thrust.

Lake currents. — Currents of either temporary or permanent nature may be present in many lakes, but in most cases they are so weak as to attract little attention. These currents may be: (1) The general movement of the water from inlet to outlet of lake, the *body current,* whose speed is slow; (2) a surface current due to prevailing winds;

[1] Martin, Bull. Amer. Geog. Soc., XLV, p. 801, 1913.
[2] Wis. Geol. Survey, Bull. VIII.

(3) return currents; and (4) surf motion, which produces a general drift towards the shore, and in some cases a shore current if the waves approach the shore line obliquely.

The first of these may be noticeable only at the head and foot of the lake, but is not necessarily a direct flow from head to foot. The second will be in the direction of the prevailing wind. The third will depend to a large degree upon the capacity of the outlet, whether it can take care of all the water that is driven towards it.

Some years ago the U. S. Weather Bureau [1] attempted to ascertain the direction of currents in the Great Lakes. It was found that in Lake Superior the return current was along the southern shore; in Lake Michigan along the eastern shore; in Lake Huron along the western shore; but in Lakes Erie and Ontario it was not so clear.

Variations in lake level. — The surface level of all lakes is liable to fluctuations, which may be gradual or sudden.

Gradual variations. — These can usually be correlated with rainfall. During a rainy season, a lake with outlet may be supplied with water by surface streams and springs faster than the outlet can carry it off, and the level of the lake rises, it may be only a few inches, or it may be several feet. Such variations are not confined to small lakes, but are sometimes quite noticeable in large ones.

It is said, for example, that "since the settlement of the Great Lakes region the level of lakes Michigan and Huron has fluctuated noticeably. Not only is there a regular seasonal fluctuation of about one and one-half feet (high water coming in June or July, and low water in mid-winter), but there are greater changes through periods of several years. In 1886 Lake Michigan was about two feet higher and in 1896 nearly three feet lower than in 1906. At high water in 1838, the same lake stood nearly six feet higher than at low water in 1896. When these secular changes of level are plotted next to a rainfall curve [2] the connection between periods of unusual rainfall or drought and periods of high or low water is evident." [3]

Sudden variations. — Lake waters are sensitive to changes of atmospheric pressure. It is sometimes noticed that in calm weather the lake level may show a variation of several feet in less than an hour. Such oscillations are known as *seiches*.[4] Of course on small lakes the *seiche* is smaller than on large ones and in many it is hardly appreciable. In addition to these, rhythmical pulsations producing a difference in level of as much as four or five inches during calms, unaccompanied by

[1] Bull. B, 1894.

[2] Lane, A. C., Mich. Geol. Survey, VII, Plate V.

[3] Atwood and Goldthwait, Ill. Geol. Survey, Bull. 7, p. 68, 1908.

[4] Perkins, American Meteorological Journal, Oct., 1893.

variations in atmospheric pressure, have been observed, but these are little understood (Russell).

Effect of strong wind. — If a strong wind blows over a lake surface for some time in one direction, the water is forced towards one end, resulting in a marked difference in level at the two extremities of the lake. In the case of Lake Erie, this difference may sometimes amount to as much as 15 feet.

Temperature of lakes. — Lake waters may be warmed, either by the sun's heat, or by contact with the air, but since water is a poor radiator as well as a poor conductor of heat, it does not respond to atmospheric temperature changes readily. A shallow lake may be warmed to the bottom by the summer's heat, and equally chilled by the winter's cold, although its temperature will be more uniform than that of the air.

The subject of the temperature of ponds and lakes is of considerable practical importance, where these are to be used for water supply, since it is desirable to obtain water not only of good quality, but sometimes at a uniform temperature.

In deep ponds (say, those deeper than 50 feet), the temperature changes may produce or prevent vertical currents at different seasons, which often exert an important influence on the quality of the water at different depths.

If in a given lake a series of temperature determinations be made at different depths throughout the year, it will be found that the shallower layers of water show the greatest variation, warming in summer and cooling in winter, while at greater depths, beginning even as low as 50 feet, the change from season to season is comparatively slight.

Even during warm summer weather, the deeper layers of a fresh-water lake may be quite cool. This is due to the fact that water is densest at 39.2° F., and the water which becomes cooled in winter sinks to the bottom. Moreover, water is a poor conductor of heat; hence, the cold lower layers are not warmed in summer. This difference in weight of water at several temperatures above and below its point of maximum density is shown by the following figures.

Temperature of water.	Density.
Degrees F.	
32	0.99987
39.2	1.00000
50	0.99974
70	0.99800
86	0.99577

In a pond less than 25 feet deep the bottom temperature does not differ much from the surface, for such shallow ponds are stirred by winds and the temperatures kept equalized. In deeper ponds or reservoirs the conditions are quite different. Thus in Lake Cochituate, Mass., for example, it is noticed that from the time of breaking up of the ice in March, the surface warms considerably more than the mid-depths and bottom, and that after September the surface temperature drops rapidly.

When the surface freezes over about January 1st, the bottom temperature is near 39.2° F. or even lower. The several layers of the lake lie in order of density, the temperature increasing gradually upwards, until within a few feet of the surface, when it suddenly falls to the freezing point, and so the water remains until the ice breaks up in April. Then the warming of the surface to the same temperature as the bottom, causes unstable equilibrium, circulation begins from top to bottom, and this is called the *working* or *overturning* of the lake. This is followed by a period of *stagnation* until about the middle of November when a second and stronger period of overturning begins.

The effects of stagnation are of importance in relation to municipal water supplies. During stagnation, if there is much organic matter in the lake, it collects in the lower quiet layers, and decay continues until all the oxygen is used up. The water gets darker, and has a bad odor. Free ammonia and other decomposition products accumulate. With the overturning of the lake in autumn this decayed matter is brought to the surface.

The phenomena just referred to may be lacking in: (1) A lake that is free from organic matter; (2) one so large that the organic matter brought in by feeding streams is completely oxidized; and (3) in a large artificial reservoir constructed on sanitary principles. It is however rare to find a lake in which the water at the bottom is as pure as that at the surface, at the end of summer.

In deep lakes covered with ice in winter, there are two lines or curves of profile which confine the variations of temperature within certain limits — the winter curve and the summer curve. These curves very nearly meet at the bottom if it is a deep lake, and are separated by a considerable interval as the lake becomes more shallow. Recognition of the phenomena described above will enable the water-works engineer to locate the off-take pipes so as to obtain water with regard to uniformity of temperature and purity. In artificial reservoirs of depth a low off-take may be provided for drawing off the impure water.

Composition of Lake Waters

The waters of lakes may show a wide range in composition. Those of fresh-water lakes, that is, those having an outlet, do not differ so much from river waters, although of course a lake receiving tributaries

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of Cayuga Lake at Ithaca, N. Y., they are over 400 feet thick.[1] At the head of Seneca Lake at Watkins, N. Y., the delta material has encroached upon the lake for two miles and the filling is over 1000 feet thick. Kootenay Lake in British Columbia has been filled in for a distance of several miles at its head or southern end with the sediments deposited by the Kootenay River. The delta built by the Rhone into Lake Geneva is several miles in length, and has been lengthened nearly two miles since the time of the Roman occupation (Chamberlin and Salisbury).

Another less important process of lake filling is by the accumulation of bog lime on the lake bottom, but this is slow, and to be looked for only in regions of calcareous waters, such as occur in some of the northern central states. The deposits thus accumulated sometimes underlie several hundred acres to a depth of 10 or 20 feet, and are often of sufficient purity to be of commercial value.

Filling by plant growth is a widespread and sometimes important process. Around the edge of many ponds there is a growth of water-loving plants, which gradually extends out towards the middle of the lake as the water becomes shoaled by the deposition of sediment.

By a combination of these two processes the pond may be gradually converted into a swamp. Many swamps and bogs are the last stage in lake obliteration. Consequently in section they often show an upper series of layers of muck or peaty material, and a lower series of sand and mud, or sometimes bog lime, the whole more or less softened by water. (See further, p. 300.)

Obliteration by lowering of groundwater level. — As noted elsewhere, the lake surface may coincide with the groundwater level. Any cause which tends to permanently depress the level will operate to destroy the lake. In some cases the opening of land for agriculture, with the clearing off of forests and consequent increased run-off, may be an active cause. This lowering of the water level will be most noticeable in porous, gravelly, or sandy formations.

A case in point is seen in southeastern Portage County, Wisconsin,[2] where the level of the groundwater has been lowered to depths varying from a few feet up to 40 feet since the region was opened to agriculture. It is a noteworthy fact also that in this area, where the groundwater has been appreciably lowered, the lakes have become greatly contracted and many of them are entirely extinct. Most, if not all, of these contracted lakes, long ago lost their outlets and their bottoms do not contain an appreciable amount of filling due to wash or to organic agencies. The natural inference is, therefore, that these lakes are being destroyed by the

[1] Part of this is glacial drift.

[2] Weidman, Wis. Geol. and Nat. Hist. Surv., Bull. XVI, p. 613, 1907.

same causes which have operated to lower the level of the groundwater of the area. In those parts of the area where the underlying formation consists of an abundance of clay or other impervious rock, where little change in the level of the groundwater has been wrought by cultivation, this process of lake extinction is relatively unimportant."

Extinct lakes. — We find records in many parts of the country of preëxisting lakes, some of them of vast size. In some cases they occupied natural basins of the earth's crust, but in other instances they were evidently due to obstruction of the surface drainage by the ice sheet which once covered the northern states, and they remained as long as the cause did.

The former existence of these lakes is recognized in various ways. Sometimes we find a natural basin partly filled with lake sediments, forming an extensive flat, with characteristic fossils present in the beds.

In other cases the former existence of the lake is recognized by old shore lines formed by wind, stream, and wave action. Not only these forms of shore lines are shown but there may also be preserved spits, hooks, bars, deltas, and beaches as in the ancient Lake Bonneville, the ancestor of the present Great Salt Lake, in Utah.

The waters of the Great Lakes formerly covered a much larger area than they do now as their outlets were closed up by the continental ice sheet. Their old shore lines sometimes serve as natural grades for roads, the well-known Ridge road along Lake Ontario being one.

Swamps

A swamp may be defined as a land area where the ground is saturated with water during most of the year, and the land not deeply submerged.

Swamps occur in different situations, but a majority of them are nearly or quite level, yet they may be found on the slopes of hills and mountains.

They are often associated with lakes, seas, or rivers, and every gradation may be found between lakes and swamps, and between swamps and uplands.

Swamps may result from either poor drainage, impeded percolation, or checked evaporation of the surface water. A level land surface may prevent thorough drainage, impervious soil may retard percolation, and dense foliage may check evaporation. In any region where the excess surface water is not disposed of by the above processes, the ground is liable to become swampy and may remain so for an indefinite time.

Kinds of swamps. — Swamps may be divided into two groups (Ref. 6): (1) *Inland* or *fresh water* swamps, and (2) *coastal* or *salt water* swamps.

Inland or fresh water swamps. — There are several classes of these, which together with their characters are as follows:

Lake swamps. — These are formed by the filling up of a lake chiefly by vegetable matter (p. 298). They may be due either to the complete filling in of a lake by plant growth, or to the development of a floating mat of vegetation on the surface of the lake. This mat may often be several feet in thickness, but some mats as much as 70 feet thick are known. Railroads and wagon roads laid on these mats have sometimes broken through.[1]

River swamps. — Such swamps are always associated with rivers, and are usually formed in the flood plains and deltas, where they may be due to frequent overflow as well as to levelness of the surface. The following subtypes of river swamps are recognized: (1) *Oxbow* swamps, which, as the name indicates, develop by the filling in of oxbow lakes; (2) *backwater* swamps, which occupy depressed portions of a river's flood plain, and are separated from the river by natural levees. The water remains in these depressions where, by the growth of plants, swampy conditions develop; (3) *delta-plain* swamps, which are like (2), except that they develop on deltas; and (4) *estuarine* swamps, formed on a flood plain where the water is backed up by the tide.

Spring swamps. — These develop on flat tracts where spring water seeps out along some impervious formation. They may have a thin covering of peat and are often difficult to traverse.

Flatland swamps. — These occur on poorly drained lands such as are characteristic of parts of the Atlantic Coastal Plain from New Jersey southward. The great Dismal Swamp of Virginia and North Carolina, which covers 2000 square miles, and the Everglades of Florida, covering 4000 square miles, belong to this class.

Raised bogs. — This type includes swamps formed on elevated flatlands in regions of high precipitation, high humidity, and cool summers. They are often filled with growths of *sphagnum* or *bog moss*, and may be higher in the middle than around the edges. Such bogs are common in eastern Maine, Nova Scotia, Newfoundland, and the far North. The *tundra* of northern latitudes owes its swampy character to melting snow.

Coastal or salt water swamps. — Swamps of this type are commonly formed between high and low tide levels. They may be developed along the coast where protected from the waves or extend along the

[1] Davis, Mich. Geol. Surv., Rept. for 1906, p. 155, 1907.

shores of tidal estuaries. They represent a common type along the Atlantic Coastal Plain, being often of vast extent.

Swamps and engineering work. — Swampy tracts give the engineer much trouble, because the soft nature of the ground makes them hard to cross with wagon roads or railroads. In the Atlantic and Gulf coastal plains railroads often have to cross such swampy tracts for long distances.

If the deposit of plant material in such a swamp is thick, it is often difficult to get solid ground for fills or other material on which to lay tracks or ballast. Where, however, the plant growth is thin, a solid foundation of silt may be found beneath it. Swamps should therefore be carefully examined before a line of travel is constructed across them. Many an engineer who has tried to construct an embankment across them has seen his "fill" slowly sink, while the ground has risen, sometimes in waves, on either side.

An interesting case is that of a railroad built across the Apalachicola River in Florida in 1907. A trestle five miles long was needed, four-fifths of which ran through densely wooded swamps, and the rest across open marsh. The mud in places was so soft and deep that a firm bottom was not reached by spliced piles 170 feet deep. In such places ordinary length piles, closely spaced, worked for a time, but in 1918 earth was being hauled some distance to fill in the trestle.[1]

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[1] See also Slifer, W. Soc. Eng., XVIII, p. 609, 1913.

CHAPTER X

ORIGIN, STRUCTURE, AND ECONOMIC IMPORTANCE OF GLACIAL DEPOSITS

Origin and Nature of Glaciers

Glaciers are not of great importance to the engineer except in certain regions, but the work which they have performed in the past, and the deposits which they have built up are matters of considerable interest to him, and present problems in connection with various subsurface operations, such as tunneling, dam foundations, aqueduct construction, underground water supply, etc. Glacial deposits sometimes serve also as a source of materials of economic importance.

Intelligent understanding of the latter phase of the subject must be prefaced by a statement of the essential principles of the origin and work of glaciers.

Formation of snow fields. — In cold regions, such as high mountain tops, and in polar lands, the snowfall if heavy may remain throughout the year, forming a *perennial snow field.*

At any point on the earth's surface, therefore, we may find a level, — the *snow line* — above which the snow accumulates. In the tropics it is from 15,000 to 16,000 feet above sea level, in the Rocky Mountains of the United States about 10,000 feet, in the Selkirks of British Columbia about 8000 feet, while at the poles it is nearly at sea level.

The snow which collects above the snow line is disposed of: (1) By evaporation, especially in dry regions; (2) by avalanches, when the snow collects on steep slopes; (3) by melting during warm days, and (4) by glaciers, in those regions where it cannot be entirely disposed of in some of the other ways.

Change of snow to ice. — If snow accumulates on the surface in quantity, the supply exceeding the waste, the mass becomes gradually compacted by its own weight, and also by alternate freezing and thawing, so that during the day when the surface layer of snow melts, the water trickles down through the cracks or pores and freezes again. We thus get a granular mass which is between snow and ice in character, the *névé,* and this grades downward into ice.

Ice motion. — If the snow and ice of a perennial snow field accumulate in sufficient thickness, the ice begins to move, and while the exact

nature of this motion is not clearly understood, the material seems to behave much like a viscous body. Such a mass of moving ice is called a *glacier*.

Conditions essential to the formation of glaciers. — These are: (1) Sufficient atmospheric moisture; (2) temperature low enough during a part of the year to precipitate the moisture as snow; and (3) snowfall during at least a part of the year in excess of the summer's melting, so that the accumulation of one year is added to the fall of the next, etc., for a period of time.

Fig. 232. — General view of an alpine glacier, the Asulkan, near Glacier, B. C. Shows the reservoir or névé, with glacier descending from it; two lateral moraines on either side, which have been left as the glacier shrank in width; the crevassed ice fall, represented by roughened dark surface, just above curve in glacier. (H. Ries, photo.)

Types of glaciers. — Depending on the conditions of accumulation we recognize three types of glaciers: (1) *Continental glaciers*, or those forming an ice cap covering a large part of a continent. (2) *Valley glaciers*, or those extending either from the edge of an ice cap as *polar glaciers* (ice tongues) or from a névé in the mountains, down into the valley forming *alpine glaciers* (Fig. 232). (3) *Piedmont glaciers*, or those formed by the merging of valley glaciers which have descended to the plain.

General features of glaciers. — A glacier, especially one of the valley type, moves faster in the middle and top than the bottom and sides, because these are retarded by the friction of the ice against the ground. While the ice flows, it is not exceedingly elastic, and comparatively slight irregularities of its bed cause it to crack. It is therefore sometimes much broken by *crevasses.*

Fig. 233. — General view of Lake Louise, Alberta, from the Victoria glacier. The lake occupies a hanging valley, its waters being held in by a moraine at the lower end. In the foreground the débris-covered surface of the Victoria glacier, with two moraines at either side beyond. Sediment carried down by glacial stream is building out a delta at head of lake. (H. Ries, photo.)

The rate of flow of the glacier ice depends mainly on the supply of snow, the grade, and the seasonal temperatures. The glaciers of the Alps advance at a rate of from two to fifty inches per day in summer and about half that rate in winter, while the vastly larger glacier which enters Glacier Bay in Alaska has a summer velocity of 70 feet per day in the middle (Scott).

As the ice stream descends from the snowfield to lower levels, it melts slowly and diminishes in thickness, but the effect of melting is most noticeable at the lower end.

If now the rate of melting back at the lower extremity and the rate of advance of the ice are balanced, the glacier appears to be stationary;

if the rate of advance exceeds the rate of melting, the ice front advances, while under reversed conditions it appears to retreat.

Effects of advancing glaciers. — Advancing glaciers may cause damage in different ways.

Glacier advance over territory not hitherto glaciated occasionally results in the destruction of forests in the path of the moving ice, but such cases are comparatively rare in modern times, although it has been noticed in Alaska.

In some instances a glacier may in its advance cross a valley, damming the stream occupying the latter. There is then danger of the ponded water becoming suddenly released. Thus Geikie [1] states that "the valley of the Dranse in Switzerland has several times suffered from this cause. In 1818, the glacial barrier extended across the valley for more than half a mile, with a breadth of 600 feet and a height of 400 feet. The waters above the ice dam accumulated in a lake containing 800,000,000 cubic feet. By a tunnel driven through the ice the water was drawn off without desolating the plains below."

Marginal lakes held between the edge of the glacier and the moraine, or rock walls are not uncommon, and the change in position of the glacier sometimes permits their sudden release. There are many cases of damaging floods from the breaking of dams of marginal glacier lakes. At Valdez, Alas., a few years ago such a flood swept away many houses, and on the Copper River Railway, in Alaska, a portion of a trestle was swept away.[2]

An interesting case of trouble caused by living glaciers is found in Alaska, along the line of the Copper River and Northwestern Railroad. The road, which has its terminus at Cordova, runs eastward across the great delta of Copper River, and here shifting glacial streams made railroad building very difficult, for the river is subject to great and rapid fluctuations of volume and load, so that quicksand bottom, erosion, deposition, channel shifting, and floating ice, all add to the engineers' problems. Farther up the line where the Niles Glacier has pushed across the valley, crowding Copper River to one side, the road was blasted out of the steep rock wall above the river, and the track here is exposed to rock and snow slides. Still farther up the route, the Allen Glacier was found to project entirely across the main valley, and the engineers decided to build the road on the glacier itself. They accordingly blasted out a grade across $5\frac{1}{2}$ miles of a stagnant, moraine-veneered, tree-covered ice mass. Ice lies beneath the ties, and future melting of it will cause slumping and repeated grading. If the glacier begins to advance there will be more trouble.[3]

During the Glacial Period the continental ice sheet of North America in several

[1] Textbook of Geology, 3rd ed., 1893, p. 382.

[2] Private communication from Maj. L. Martin.

[3] Martin, Bull. Amer. Geog. Soc., XLV, p. 801, 1913; Nat. Geog. Mag., XXII, p. 541, 1911; Tarr and Martin, Annals Assoc. Amer. Geog., II, p. 25, 1913.

cases formed a dam across valleys occupied by lakes, causing the water surface to rise as much as several hundred feet above its normal level. A fine example of this is seen in the valley of Cayuga Lake in New York State, where the numerous delta terraces observed at different levels on the valley slopes show the several levels at which the lake stood, while its waters were dammed by the ice during its retreat to the northward. Elevated shore lines around some of the Great Lakes were formed when their waters formerly stood at higher levels due to the same cause.

Additional trouble may be caused by streams fed by the melting snow and ice. During winter, or cold days and nights of summer, when little or no melting takes place, the streams flowing from the snow fields are sometimes of small volume, but on warm sunny days when the snow and ice melt rapidly, the volume of the streams is greatly augmented.

Care should be taken, therefore, to bear this in mind in constructing rail and wagon roads in mountain regions where there is an abundant accumulation of snow and ice.

Cases are known where roads constructed too near to the edge of a snowfed stream have been overflowed regularly on warm summer days, and in some instances undermined and washed away in places.

Glacial erosion. — Glaciers perform a certain amount of erosion which is so characteristic that it enables us to recognize the former existence of the ice, even though it has long since disapppeared. The erosive work they are capable of doing must vary since it depends on the velocity of movement, amount of rock material held in their lower layers, the pressure on the beds, thickness of ice, and character of rock surface.

Erosion may be accomplished in several ways, as follows: (1) In moving over a surface not yet traversed the ice often removes the soil or other loose materials from it. (2) Rocks and sand, partly imprisoned in the lower part of the ice, when rubbed over a bare rock surface, and held down against it under great pressure abrade the bed rock more or less, as well as polishing, scratching or grooving it in a very characteristic manner.

Glaciated rock surfaces are, therefore, sometimes very uneven, and hence in a glaciated region the bed rock often lies at a variable distance below the surface, a fact that engineers should remember in sinking foundations.

Erosion is also performed by a process known as *plucking*, which is the tearing away of joint blocks by the advancing ice.

Glacial erosion produces characteristic topographic features. Angular outlines are rounded off, and the cross-section of a glaciated valley is U-shaped with a broad bottom and very steep sides. A river valley in contrast has a V-shaped cross-section, with projecting

spurs. These latter are removed by prolonged glaciation. Lake valleys are sometimes deepened by glacial erosion, as in the case of the Great Lakes, and also the Finger Lakes of central New York.

If a main valley is deepened by glacial erosion, while its tributary is less, or but slightly deepened, the lower end of the latter will be above the former when the ice disappears, that is, the tributary will be discordant as to grade with its main valley, depending upon the inequality of deepening in the two valleys. The tributary valley is then known as a *hanging valley* (Figs. 169 and 233). Such valleys are not uncommon in some glaciated regions.

Glacial transportation. — Glaciers can transport material on their surface, within their mass and in the bottom part of the ice.

The surface load consists of rock fragments of all sizes and other débris that has fallen on to the ice from cliffs and slopes that project above it.

The bottom of the glacier is often a confused mass of ice, stones, etc., and when deposited forms the ground moraine.

The englacial drift is either débris that has fallen into cracks from the surface, or has collected on the surface of the snow, and become covered by subsequent snowfalls. Englacial drift is protected from wear by the glacier and can usually be recognized by its angular character.

Glacial Deposits

Surface moraines. — The débris which accumulates on the surface of a glacier is sometimes arranged in belts or bands called *moraines.* If the débris is heaped up in ridges on the side of the glacier it is called a *lateral moraine.* If in a parallel position but some distance from the edge it is known as a *medial moraine,* and several of these may exist on the same glacier. Such moraines are sometimes formed by the union of lateral moraines when two glaciers join.

If the edge of the glacier remains stationary or nearly so for some time, all the transported material, except that carried away by water, is dropped as the ice melts, and forms a more or less hummocky ridge at the end of the glacier, known as a *terminal moraine.*

Since ice does not sort material as does water, the terminal moraine, when not modified by escaping glacier waters, is unstratified and consists of materials of all sizes from silt and fine sand up to boulders weighing many tons.

If a glacier remains stationary for a considerable period of time, all things being equal, a moraine of large size may be built up, provided the glacier transports much material; or if during its recession the glacier

halts for a time at different points a number of terminal moraines will be formed.

When a glacier melts slowly its débris is deposited as an irregular sheet, which constitutes the *ground moraine*. This is not stratified except in those places where modified or formed by water. It consists of fine clay or sand with scattered boulders, the latter often showing scratches and is termed *till* or *boulder clay*. *Drift* is a general term applied to glacial deposits.

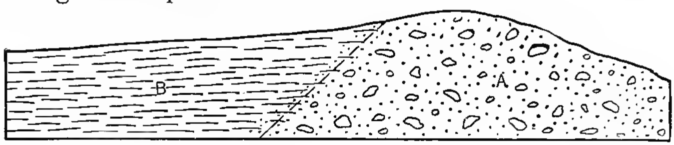


FIG. 234. — Section showing relation of outwash plain to a terminal moraine.

Nature of glacial deposits. — Glacial deposits are usually quite characteristic in appearance for several reasons: (1) The ice does not exercise a sorting action, so that we find boulders, cobbles, pebbles, sand and clay forming a confused mass; (2) the stones of the drift, although worn, are not rounded like those transported by water, but have a more or less subangular form; and (3) the stones are often striated and polished.

The moraines of preëxisting glaciers often form natural dams across valleys, obstructing the drainage, and creating lakes that serve as sources of water supply. As the material is not very permeable, little seepage results. At other times the old moraines still remain as ranges of hummocky hills extending across the country.

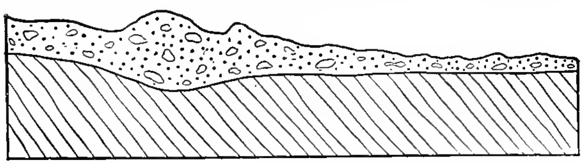
Glacial-water deposits. — The water flowing from a glacier may carry vast amounts of débris, sometimes of considerable coarseness, and deposit the latter over the surface beyond the glacier margin. If this is deposited in valleys it is called a *valley train*, but if on a more or less flat surface of large areal extent, the term *outwash plain* or *frontal apron* (Fig. 234) is applied to it. Deposits of this kind are usually distinguishable from ordinary river deposits by the fact that they often grade into moraines, and that their constituents bear evidence of glacial origin. *Eskers* are long, winding gravel ridges, deposited by streams flowing in channels in the ice, or beneath it. *Kames* are short ridges of similar material piled up by glacial streams flowing from beneath the ice, frequently against the end or terminal moraine.

Past glaciation. — Glaciers in the past have accomplished similar work, and built up the same kind of deposits as existing ones. From such evidence, therefore, as glacial erosion, smoothed and striated rock surfaces, the deposition of moraines and other glacial drift

including perched erratics of foreign rock, and general characteristic modification of the land surface (stream and interstream areas) by erosion and deposition, we can affirm that all of Canada, and the northern part of the United States were formerly covered by a vast continental glacier, which started from two or three centers to the north and moved from these centers of dispersion, probably outward in all directions. In the eastern United States it extended to the dotted line indicated on the map (Fig. 196).

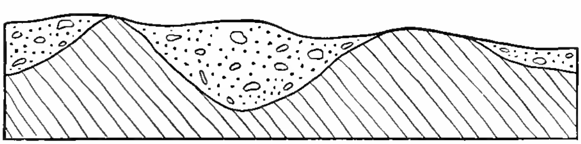
As a result of this the engineer at the present day finds himself confronted with a number of phenomena, which sometimes seem very perplexing, but whose understanding is often of vital importance from the financial standpoint. Some of these are discussed below.

Glacial drift. — The glaciated area of the United States and Canada is covered with a more or less continuous mantle of drift of variable thickness, usually being deepest in the valley bottoms and thinnest on the interstream areas. In the United States it is thickest in a broad belt a little within the margin of the drift area, which extends from central New York throughout Ohio, Indiana, Illinois, Iowa, Minnesota and Dakota, and thence northward to an unknown limit in Canada (Chamberlin and Salisbury).



A

Fig. 235. — Section through glacial drift and bed rock, showing how the deposition of morainal material has made the surface more irregular.



B

Fig. 236. — Section showing how the deposition of glacial drift has reduced surface irregularities.

Over any region the thickness of the drift may vary within short distances. The depth then to bed rock may be quite variable, and the drift mantle either decreases or increases the relief of the surface (Figs. 235 and 236).

The vertical range is also great, for in New York State it is found from sea level to nearly 5000 feet altitude in the Adirondacks.

The contact between the drift and the underlying rock surface is usually sharply defined for the reason that the continental glacier removed in most places the residual soil, leaving the fresh and firm underlying rock.

Many of the rocks distributed through the drift are of kinds occurring many miles to the north of where they are now found. Large ice-transported boulders many tons in weight are also found scattered over the drift-covered area, regardless of topography.

Sometimes the drift is of great thickness even in places where one might not expect it. Thus at Mineville, N. Y., one of the mine shafts sunk on a hillside passed through 250 feet of drift before reaching bed rock.

Large boulders in the drift are sometimes mistaken for bed rock in drilling, especially where wash borings are made. In sinking test holes along the line of the Catskill aqueduct for New York City the drillers on Moodna Creek struck a glacial boulder at 15 feet and reported bed rock,[1] whereas the latter was 300 feet below the surface.

Topography of the drift. — The drift presents certain characteristic topographic features, such as: (1) Depressions without outlets; (2) knobs, hills and ridges of similar size to the depressions, associated with them; (3) and ponds often formed in the depressions.

The topography of a terminal moraine is more or less characteristic. "It sometimes constitutes a more or less well-defined ridge, though this is not its distinctive feature, since its width is generally great relative to its height. A moraine 50 or even 100 feet high and a mile wide is not a conspicuous topographic feature, except in a region of unusual flatness. In such situations terminal moraines sometimes constitute important drainage divides. The surface is often characterized by hillocks and hollows, or by interrupted ridges and troughs, following one another in rapid succession, and without apparent order of arrangement" (Chamberlin and Salisbury).

Glaciation and Engineering Problems

Buried channels. — In glaciated regions many of the present streams occupy the partly or completely filled pre-Glacial valleys. During the Glacial Period their valleys or gorges became completely clogged with glacial drift so that after the recession of the glacier these streams had to cut new channels. Abundant modification of stream drainage has resulted.

In some cases a stream has sunk its channel through the thickness of drift, in others not, while in still others the deflection to one side of its former valley has enabled it to cut through into the underlying hard rock. Again others are flowing in new channels on the drift cover.

Tunneling and buried channels. — Tunnels sometimes encounter these buried channels. For example, in bringing the aqueduct tunnel

[1] Berkey, N. Y. State Museum, Bull. 146, p. 26, 1911.

from the Catskill Mountains to New York City, a number of these buried channels were encountered (Fig. 237), and it was necessary to carry the water under these by inverted siphons. The deepest was that of the Hudson Valley in the Highlands, where the tunnel had to be carried 1000 feet below sea level in order to get under the buried gorge of the Hudson.

Buried channels are also of importance in connection with underground water supply, for the gravels and sands that sometimes fill them carry a sufficient supply of good water to be drawn upon (Fig. 193).

In central New York some of the streams tributary to the lakes now occupy post-Glacial gorges, while their buried pre-Glacial channels lie at the same level to one side. One of these buried channels was used to conduct a water pipe from a reservoir to a power house farther down the gorge. In another case it was noticed during the construction of a reservoir across a post-Glacial valley that the pre-Glacial channel left the stream a short distance above the dam. Some fear was at first felt lest there might be leakage from the reservoir through this channel. It was found, however, that the latter was choked with rather dense clay.

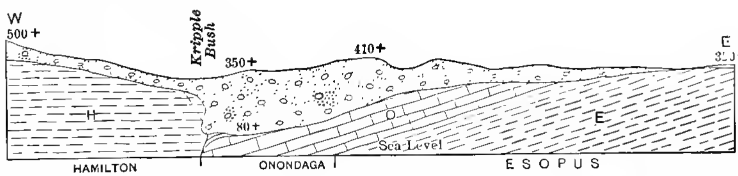


FIG. 237. — Section across Rondout Valley, N. Y., showing pre-Glacial valleys which have been filled with glacial drift. (Berkey, N. Y. State Museum, Bull. 146.)

Underground water supply. — The drift is known to contain considerable water, which is drawn upon for dug and artesian wells as discussed elsewhere. (See Artesian Water.)

Dam sites. — In the construction of dams across valleys in glaciated areas, it is sometimes necessary to construct them in glacial drift, which covers the bed rock. In such cases the drift should be carefully tested at different points to get a water-tight foundation, for the reason that within the till there are frequently pockets, lenses, or beds of sand and gravel which are permeable to water. Obviously, where several sites are available, that one will be the best which contains the densest material, thus avoiding the danger of leakage under or around the ends of the dam.

In selecting a dam site for the reservoir that is to supply the new Catskill aqueduct leading to New York City, the engineers found two locations known as the Olive Bridge (Fig. 239), and the Cathedral

gorge or Tongore site (Fig. 238), either of which seemed possible from a topographic standpoint. Both, however, were carefully explored by trenches, shafts, and boreholes.

In each case it was found that the bed rock had an uneven surface, that there was a buried gorge of Esopus Creek, and that the glacial deposits were over 200 feet thick in the narrow valley, as shown by sections.

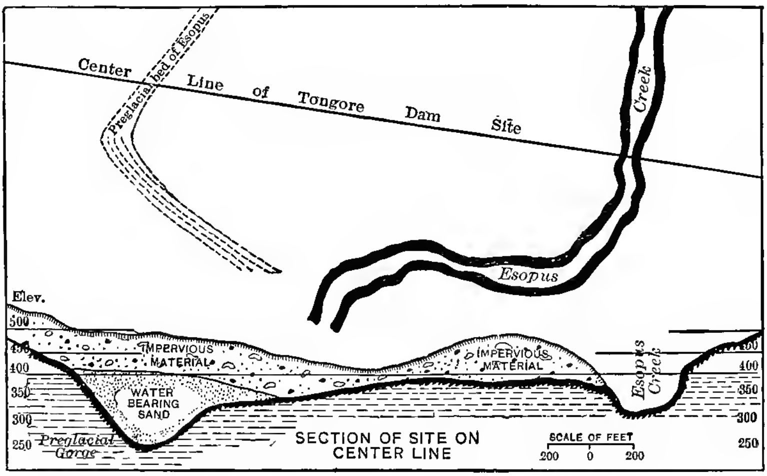


Fig. 238. — Section through Tongore dam site, tested for Catskill, N. Y., aqueduct. (After Berkey, N. Y. State Museum, Bull. 146.)

The Olive Bridge site was chosen because of: (1) Higher bed rock surface throughout; (2) more uniform and impervious character of the drift; (3) more massive cross-section of the drift barrier for the foundations; (4) perfectly tight contacts of till and bed rock; and (5) restriction of more porous materials to the higher levels of the section.

Quarrying operations. — The continental glacier has indirectly affected quarrying operations. Thus in the states lying within the glaciated area, the residual soil and partly-decayed rock have been removed, and the quarryman usually finds sound stone at bed rock surface, but south of the glaciated region, the residual soil and partly-decayed rock still remain, and stripping to some depth is often necessary to reach fresh rock.

Water powers. — Attempts are sometimes made to show that the continental glacier was an indirect cause in the development of abundant water power. However, this view may be a somewhat exaggerated one, as many important water powers exist and are being developed outside of the glaciated area. It is true, of course, that a con-

siderable fall is sometimes obtained in post-Glacial valleys, and at the mouth of hanging valleys, which can be used for power purposes.

Economic materials in glacial deposits. — Owing to the diversified nature of the glacial drift, it contains a variety of materials of economic value. The masses of clay found in moraines and glacial-lake basins can be and are used frequently for brick manufacture. Beds of sand and gravel occurring in the moraines and modified drift are employed for mortar work, railway ballast, road material, concrete, cement blocks, foundry molds, sand-lime brick, glass manufacture, and filter plants.

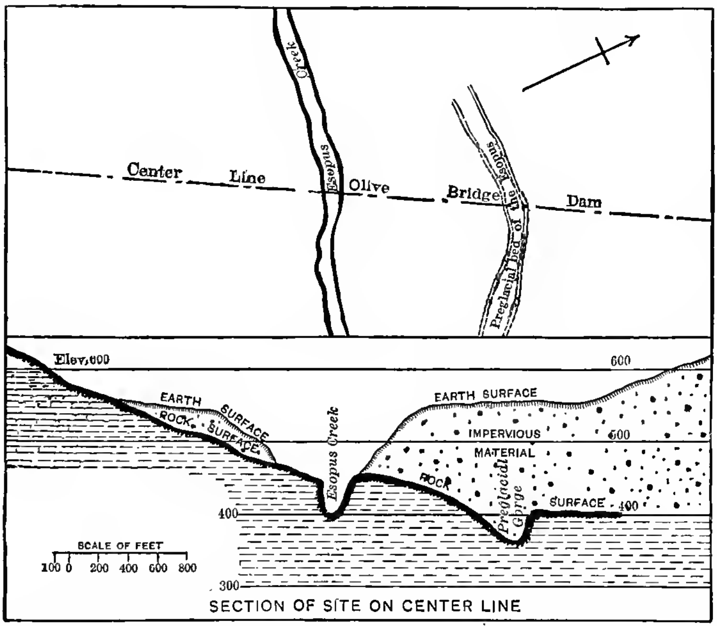


FIG. 239. — Section through Olive Bridge dam site, tested for Catskill, N. Y., aqueduct. (After Berkey, N. Y. State Museum, Bull. 146.)

References on glacial deposits

1. Atwood, — U. S. Geol. Surv., Bull. 685, 1918. (Relation of glacial deposits to reservoir sites.) 2. Berkey, C. P. — Geologic Features and Problems of the New York City (Catskill) Aqueduct, N. Y. State Museum, Bull. 146, 1911. 3. Chamberlin & Salisbury, — A College Textbook of Geology, New York, 1909. (Henry Holt & Co.) 4. Salisbury, R. D., — New Jersey Geol. Surv., Final Report, V, 1902.

Many of the geological surveys of states lying within the glaciated region have published special bulletins or reports on their glacial deposits. The United States Geological Survey has also issued a number. Most of these are written from the purely geologic standpoint. They may be of value to engineers in the areas of which they treat, since they give information regarding the thickness and character of the drift.

CHAPTER XI

ROAD FOUNDATIONS AND ROAD MATERIALS

In the construction of roads, the problems which the engineer has to deal with are partly geologic and partly of a purely engineering character. In former years only the engineering phases of the work were considered, but more recently the geologic problems have also been given serious attention. The geologic phases of the work include a consideration of (1) the natural conditions which may affect the permanence and stability of the road bed, drainage, etc., and (2) the kind, character, variation, and distribution of the rock to be used for the road, whether sand, gravel or crushed stone. What may be said under the first head applies equally well to rail and wagon roads, as both are affected by the same set of geological conditions, and unless specifically stated to the contrary this can be understood to be so.

Road Foundations and Cuts

Rock formations. — The rocks on which a road has to be laid or through which cuts have to be made may be either (1) unconsolidated, as clay, sand, gravel, boulder till or peat, or (2) consolidated, as various igneous, sedimentary, or metamorphic rocks.

Filled depressions. — Where a road has to cross depressions, such as valleys or lake bottoms, the bed rock often does not reach the surface, and there may be a variable depth of unconsolidated material of varying bearing power underlying the bottom of the depression.

Stream valleys are often filled in with beds of gravel, sand, or even clay. Lake depressions may be filled with sand and clay, or by peaty material which is sometimes only a thick mat resting on water (see Swamps, p. 299).

It is therefore of the highest importance that such material should be carefully investigated in advance whether it is to serve as a foundation for bridge piers or is strong enough to carry a fill for a road.

Tightly packed dry sand or gravel may support considerable weight, but wet sand, clay, or peat have much less bearing power, so that if loaded down with the weight of a fill the material under it settles while the ground on either side rises up in waves.

The bearing power of dry sand for example is given as 2 to 4 tons per square foot, while that of wet sand is only ½ to 1 ton per square foot.

Piers for railroad bridges are often of large size, those for wagon bridges not usually as great, but in either case it is essential that they rest on firm ground. The material on the sides of a valley is sometimes of the character of slide material, which does not remain firm under great weight.

In other cases the beds may dip towards the stream, and contain slippery layers here and there in the section. If now a large bridge pier is placed on such a mass, the weight of it may cause movement along some of the slip planes, unless the precaution has been taken to prevent it.

Exposures in slopes. — If a road is constructed along a slope or has to pass through an artificial cut, the character and structure of the rock must not be overlooked.

In either case there is at least some excavating to be done, and consequently removal of some of the support that the material had. The question therefore arises whether it will stand in its unsupported condition, or with some of its former support removed.

Clay often has a high absorptive power for water, so that it softens and slides when wet. Even if it does not get wet enough to slide, it may absorb enough water to make it swell, so that if it underlies the road the latter may be heaved up. Drainage often serves to prevent sliding and swelling.

Gravel and sand may stand when first excavated, but are liable to crumble down eventually unless quite porous and well cemented. Sand is usually quite permeable.

The permeability and capillarity of these materials can be tested by bringing a sample of known volume in contact with a known volume of water, and noting the time that the latter takes to pass through the former. For the permeability test the water should be placed above the material, and for the capillarity test, below, but in contact with it.

Boulder-till may stand up for several years in a dry climate, but slakes down rather easily in a moist one.

Hard rock often stands up in a vertical face, but sliding is apt to be initiated by structural features such as joints or bedding planes, especially if these slope towards the excavation (Chapter VII).

Another cause of sliding in a cut is the presence of alternating hard and soft beds. Take the case of sandstone interbedded with soft shale. As the latter weathers back, the sandstone beds are robbed of their support and fall. The consequences of sliding may be much

more serious in railroad than in wagon road cuts, so that the former often have to be carefully watched.

Road Materials

Raw materials used for highway construction. — These include clay, sand, gravel, glacial boulders, and crushed stone. The properties of these are discussed in the following pages of this chapter, but their mode of occurrence is treated in Chapter II.

The different kinds of unconsolidated and consolidated rock employed in highway construction are rarely transported for long distances, local sources of supply on the contrary being usually drawn upon. It therefore frequently devolves upon the engineer to carefully examine these local sources with reference to the quantity and quality of the best material, its accessibility and thickness of overburden.

The engineer engaged in road construction or the preparation of specifications should be familiar with at least the common kinds of rocks and avoid specifying rocks which may be of rare occurrence.

Before beginning road construction it is often desirable to make a survey of all possible sources of supply, with reference to their quality and conditions affecting development.

Clay

Clay is sometimes used for roads, but the different deposits available vary widely in their characters. Some are exceedingly sticky when wet, and dry to a hard, caked, cracked mass, like the *gumbo* of the western and southwestern states, or the *black waxy* soil of Texas. When very wet these are almost impassable. Other clays are sandy, and do not get quite so sticky. Under continued traffic clay roads, when dry, wear down to a dust that is equally disagreeable.

Much better results are obtained by using a sand-clay mixture, in which case the clay fills the voids between the sand grains. Roads of this type are common in many parts of the South, especially in the Coastal Plain region, and give excellent results, provided the sand and clay are well mixed and the road is properly drained. The clay, which should have a low air shrinkage, forms from 10 to 30 per cent of the mixture and acts as a binder for the sand. In some districts burned clay has been used for wagon roads, but its use is not widespread.

Sand

Under this heading is included material ranging from 10 to 200 mesh in size. Grains under 200 mesh are called silt and range from 0.07–0.01 mm. in diameter.

Silt alone when dry has no cohesive quality, but when moist has some supporting power, and when saturated with water acts like quick sand. It alone is of no value for road purposes.

Sand alone is not of value as a road material although when moist it packs pretty solid. It is widely used in mixtures as in sand-clay roads, gravel roads, asphalt and concrete pavements, etc.

Sand grains vary greatly in their size, shape, and mineral composition (p. 69), facts which the road engineer should not overlook. In sand-clay roads, where the sand forms as much as 70 per cent of the mixture, sand grains of 20 to 60 mesh have the best interlocking strength.

The interlocking power is important, and will depend on the degree of angularity and irregularity of the grains. Mica and organic material are undesirable constituents, but iron oxide serves as a binder.

For sheet asphalt pavements the sand (Ref. 1) should be hard, moderately sharp, clean, of proper mesh size and siliceous.

The following figures give standards of mesh composition for paving sands.

Mesh	Light traffic	Heavy traffic
	Per cent	*Per cent*
Passing 200 mesh	0– 5	0– 5
" 100 "	10–15 } 18–25	10–25 } 25–40
" 80 "	6–15 }	10–20 }
" 50 "	10–40	5–40
" 40 "	10–30	5–30
" 30 "	10–20	10–15
" 20 "	10–15	5–10
" 10 "	5–12	2– 8
" 8 "	0– 5	None

Sources of sand. — Sand may be of residual or sedimentary origin, the latter including water, wind, or glacial deposits.

Residual sands are comparatively rare, and are not likely to be composed always of resistant minerals. They will commonly be angular. Sea beach sands are not usually regarded as desirable because of their smooth grains and texture (commonly between 50 and 80 mesh). Lake-beach sands are less rounded than those from the seashore, and may show a wider range of sizes than those from sea-beaches. The former are often used in paving work. River sands are the most widely used, but show considerable lithologic variation.

Bank sands, as understood by the engineer, include deposits formed by glacial action (p. 308), sand dunes (p. 69), and those made by streams at an earlier date. They hence exhibit considerable varia-

tion in mineral composition and texture, even in the same bank. Loamy layers may be interstratified with sand beds in the glacial and river deposits. Selective excavation may be necessary both on account of texture and the need of getting clean material.

A knowledge of geology will often be of great assistance in prospecting for sands.

Gravel

This includes all unconsolidated material that will not pass a 4-mesh sieve. It may occur: (1) As a constituent of modified glacial drift; (2) as a stream deposit; (3) as extensive deposits laid down by water not necessarily confined to valleys; (4) as delta deposits; and (5) as beach deposits. Gravels then are usually of the transported type, so that the pebbles are more or less rounded. Gravelly deposits of a residual character are known, and are used especially in the South, where the chert, much used in Alabama, is commonly referred to under this name. As found in nature gravel is seldom clean, but is mixed with more or less sand and clay, which if abundant is removed by washing and screening. A gravel composed only of smooth pebbles with no sand is undesirable as it lacks binding quality.

Most gravels have too many large stones or too much sand, and ideal gravels are hard to find; however there are many that can be used with a little mixing.

The pebbles vary from rounded to angular and the latter, other things being equal, compact under traffic more rapidly than the former, and thus will aid in producing a firm road bed in a short time.

Special attention should be given to the lithologic character of the pebbles, for they vary greatly in different regions. Thus in one area they may be all quartz, in another chert, in still another limestone, or in a fourth they may be largely rocks composed of silicate minerals. This difference in lithologic character will seriously affect the value of the gravel for road purposes.

Blanchard (Ref. 1) gives the following requisites for a good gravel: (1) Pebbles mostly of hard stone; (2) good abrasive resistance; (3) at least 75 per cent of pebbles from $\frac{1}{4}$ to $1\frac{1}{2}$ or 2 inches in size; and (4) about 25 per cent of sand or clay mixture of which 8 to 15 per cent should be clay or similar binding material as iron oxide or calcium carbonate.

Broken Stone

The broken stone used for roads may be of almost any kind of rock, included under the three groups, igneous, sedimentary, and metamorphic. The mineralogical composition and textural properties of the

different kinds have already been given in Chapter II and need not be repeated here.

Attention should, however, be called to the fact that the minerals found in rocks may be divided into two classes, viz., primary and secondary. The former includes such minerals as quartz, feldspar, pyroxene, amphibole, biotite, muscovite, calcite, dolomite, garnet, olivine, etc.; the latter, minerals like chlorite, kaolinite, sericite, limonite, serpentine, epidote, and sometimes calcite and quartz. A small amount of some of these secondary minerals may increase the binding power of the rock, but an excess is likely to have the opposite effect.

The weathering qualities are important and depend primarily on the mineral composition, rather than on the hardness and toughness.

Rocks whose grains are loosely held together lack coherence, and may have high porosity, as well as low abrasive and crushing resistance. Hard rocks, whose grains are tightly interlocked are stronger and better than the preceding class, even though they may be of low cementing value. Easily soluble rocks, such as limestones, are also bad. Many of the strongly foliated metamorphic rocks, such as chlorite and mica schists, are undesirable, because owing to their softness and structure they wear easily.

Properties of Crushed Stone

The properties that are commonly considered in the selection of stone for roads are: (1) Abrasive resistance; (2) hardness; (3) toughness; (4) cementing value; (5) absorption; and (6) specific gravity.

"Resistance to wear." — Resistance to wear is a special property in a rock, and although it depends to a large extent upon both the hardness and the toughness of the rock it is not an absolute function of these qualities.

The per cent of wear in the table refers to the dust and detritus below one-sixteenth of an inch in size worn off in the abrasion test.

The French coefficient of wear is obtained by dividing 40 by the per cent of wear. Thus a rock showing 4 per cent of wear has a French coefficient of wear of 10. The best wearing rocks give a coefficient equal to about 20, and this number has been adopted as a standard of excellence. In interpreting the results of this test a coefficient of wear below 8 is called low; from 8 to 13, medium; from 14 to 20, high; and above 20, very high. Rocks of very high resistance to wear are only suited for heavy traffic.

Hardness. — By hardness is meant the resistance of a rock to the grinding action of an abrasive agent like sand.

In order to report these results on a definite scale which will be convenient the method has been adopted of subtracting one-third of the resulting loss in weight in grams from 20. Thus a rock losing 6 grams has a hardness of 20 − 6/3 or 18. The results of this test are interpreted as follows: Below 14, rocks are called soft; from 14 to 17, medium; above 17, hard.

Toughness. — By toughness is meant the resistance a rock offers to fracture under impact; such, for instance, as the striking blow given by a shod horse. The height in centimeters of the blow which causes the rupture of the test piece is used to represent the toughness of the specimen. Results of this test are interpreted so that those rocks which run below 13 are called low; from 13 to 19, medium; and above 19, high.

Cementing value. — By cementing value is meant the binding power of the road material. Some rock dusts possess the quality of packing to a smooth, impervious mass of considerable tenacity, while others entirely lack this quality.

The ground rock is molded with water into briquettes, which when dry are broken by the impact of a small hammer, the number of blows struck being a measure of the cementing value of the dust. The test is interpreted so that cementing values below 10 are called low; from 10 to 25, fair; from 26 to 75, good; from 76 to 100, very good; and above 100, excellent.

Most road stones have cementing values between 10 and 200. If under 25 the rock is considered unsuited for water-bound macadam. If over 75 it will bind readily into a firm mass.

Weight per cubic foot. — The weight per cubic foot refers to the weight of the material in the form of a solid and not as broken stone.

Absorption. — The absorption is expressed in pounds of water absorbed per cubic foot.

Specific gravity. — This is determined in the usual manner.

Results of tests. — In the accompanying table are given the average, maximum, and minimum figures obtained for the several tests on different rocks, as published by the U. S. Office of Public Roads.

Significance of tests.[1] — The attrition loss seems to be conditioned by texture, mineral composition, and degree of freshness of the minerals. The hardest and toughest stones seem to be those containing an abundance of quartz and having a dense fine-grained texture.

The abundant development of secondary minerals produced by weathering is undesirable, but the presence of secondary minerals produced by deep-seated processes, such as uralitic hornblende (p. 12), seems to strengthen the rock.

The number of different kinds of rocks used for road material is very great, and the tests of each kind considering the maximum and minimum figures show considerable range. One may, therefore, raise the point, whether in engineering specifications it would not be better to demand that the material meet certain tests, rather than to simply call for rock of a certain kind or its "equivalent."

[1] Bull. 31, U. S. Bureau Public Roads, has been largely drawn upon for these data.

Maximum and Minimum Results on Rock Samples, Corrected to January 1, 1910

Name.	Specific gravity.	Weight — Pounds per cubic foot.	Water absorbed — Pounds per cubic foot.		French coefficient of wear.		Hardness.		Toughness.		Cementing value.	
	Av.	*Av.*	*Max.*	*Min.*	*Max.*	*Min.*	*Max.*	*Min.*	*Max.*	*Min.*	*Max.*	*Min.*
Andesite	2.70	168	6.59	0.05	26.0	4.9	19.4	7.9	44	6	500+	11
Basalt	2.85	178	6.32	0.04	30.4	2.7	19.2	5.9	39	6	500+	4
Chert	2.55	159	11.10	0.26	14.6	1.4	19.7	12.7	26	5	500+	2
Conglomerate	2.60	162	3.71	0.60	11.6	3.2	18.4	9.3	10	10	500+	20
Diabase	2.90	181	2.73	0.03	36.4	6.4	19.4	12.3	54	4	500+	2
Diorite	2.85	178	1.03	0.05	25.0	5.5	19.4	16.6	38	5	148	5
Dolomite	2.75	172	9.40	0.07	33.3	2.2	18.4	1.8	27	3	179	9
Felsite	2.65	165	3.13	0.02	21.3	11.8	....	....	....	....	....	....
Gabbro	2.95	184	0.97	0.04	30.8	6.8	18.8	16.2	23	9	115	6
Gneiss	2.75	172	1.24	0.02	23.0	2.4	19.3	9.0	25	2	110	1
Granite	2.65	165	2.77	0.04	37.0	1.6	19.6	13.6	33	2	255	2
Limestone	2.70	168	13.22	0.02	21.7	1.2	19.1	0.0	25	2	500+	10
Marble	2.75	172	1.04	0.10	16.0	2.8	17.3	7.1	23	3	85	15
Quartzite	2 70	168	1.89	0.05	24.5	5.3	19.7	16.5	30	5	45	0
Rhyolite	2.55	159	7.15	0.03	23.0	4.1	19.7	15.3	42	6	500+	10
Sandstone	2.65	165	11.60	0.02	40.8	1.0	19.5	0.0	60	2	500+	1
Schist	2.90	181	1.35	0.06	31.7	2.2	19.0	0.9	35	3	232	5
Shale	2.65	165	4.84	0.50	12.6	2.5	17.7	13.9	12	3	367	28
Slate	2.75	172	2.10	0.05	24.4	3.2	19.7	1.1	56	1	500+	1
Syenite	2.70	168	4.21	0.08	23.5	2.8	19.2	17.3	34	8	375	16

Qualities of Different Classes of Rocks

Igneous rocks. — The order of toughness beginning with the highest is: (1) Trap, including basic plutonic rocks, and basic volcanics such as andesite, basalt, diabase, etc.; (2) felsite and acid representatives of the same type as rhyolite, quartz porphyry, etc.; (3) gabbros and related basic plutonics; and (4) granites, syenites, etc.

The order of abrasive resistance beginning with the highest is: (1) Diabase and basalt; (2) diorite and gabbro; (3) andesite and rhyolite; and (4) granite.

The cementing value is greater in the basic plutonic rocks than in the acid ones, and higher in the volcanic rocks than in the coarse-grained plutonic ones.

With regard to the relation between road making value, mineral composition, texture, and alteration the following seems to hold: Rocks with a high percentage of augite or hornblende seem to be more durable than those with a high percentage of mica, and fine-grained holocrystalline rocks appear more durable than coarse-grained ones. Secondary alteration to epidote and uralite increases the durability of plutonic rocks, while alteration to kaolinite and chlorite tends to decrease the durability. The cementing value in holocrystalline plu-

tonic rocks varies inversely as the quartz content and directly according to the amount of secondary alteration.

In volcanic and plutonic rocks the relation between mineral composition and durability is shown by the lower percentage of wear and greater durability of diabases, basalts, and trachytes with little or no glass, and the rhyolites where glass is present. The toughness is due to finely crystalline constituents which interlock. In general, fineness of grain and absence of large cleavage planes account for greater toughness.

Sedimentary rocks. — Limestones and dolomites are by far the most useful for road construction. They are only of moderate durability and not suited for heavy traffic except with bituminous or cement binders, and in the latter cases they appear to have given better results than tougher igneous rocks. The finer and more even-grained limestones and dolomites are the most durable. Most limestones show good cementing power in the road bed, in fact better than often appears in laboratory tests.

Sandstones are not widely used, because the strength and cementing value are largely functions of the strength and amount of the cement, although the shape of the grains also plays a rôle. Some clayey, calcareous and ferruginous sandstones have made satisfactory water-bound macadam roads, but most sandstones are not of much value. Bituminous sandstones and limestones are in a class by themselves.

Shales are not as a rule suited for road work, although hard ferruginous ones sometimes serve well under light traffic.

Cherts have been used with success in parts of the South.

Metamorphic rocks. — Gneisses are supposed to be less durable than their unmetamorphosed equivalents, but still there are some good gneisses which were derived from igneous rocks.

Hornblendic schists usually give better results than mica or chlorite schists.

Marble, quartzite, and slate are not in general suited for road aggregates, although the quartzites, though lacking in cementing value, are quite durable.

Stone Blocks

Blocks for roadways are usually made of granite, although sandstone, quartzite, and trap are sometimes used. Their essential properties are resistance to weather, and sufficient abrasive resistance to prevent their wearing round and smooth under traffic.

Granite is preferred for blocks because it splits easily. Trap is

harder and tougher and hence does not cut so readily, neither does it wear round as granite does, but more uniformly, even though at times somewhat readily. Sandstone cuts easily, and in New York State the Medina sandstone as well as the Potsdam quartzite are said to have been used for pavements (Ref. 1).

Glacial Boulder Deposits

In glaciated regions glacial boulders, often called field stone, are found strewn over the fields or piled up in fences, and may form a valuable and cheap source of road material (Ref. 4).

A disadvantage of this type of road surfacing material is its uneven character, which may cause one section of a road to wear more than another, or even produce uneven wear in the same section of road.

Boulder deposits in some areas may be made up largely of one kind of stone, but in many others they represent a number of varieties, and the proportion of the different kinds may vary from field to field or from wall to wall.

If such material is to be used it should therefore be carefully sampled, rejecting badly weathered pieces. The walls and piles of stone in an area under examination are plotted, and the quantity calculated. Estimates are also made of the boulders above and below one foot in diameter, as well as of the composition by counting the boulders of each variety present in a section of wall.

The true average composition of a group of walls is obtained from the composition of the individual walls, giving proper weight to the yardage included in each individual estimate.

Only good firm stone is used in any case, but if less than 10 per cent is composed of schist, shale, friable sandstone, or badly weathered stone, the material may be considered fit for the foundation course of a trunk highway (Ref. 6).

Petrographic Examination of Road Materials

The examination of road materials under the microscope is a means of obtaining information regarding the shape, size, mineral composition, purity and character of the surface of sand grains.

With thin sections of rock the microscope shows the kind and relative proportions of the different minerals present, the shape and manner of interlocking of the grains, degree of alteration or decay, presence and arrangement of microscopic fractures, cleavages, and pores.

Even a polished surface will when wet give considerable information when examined with a hand lens (Ref. 1).

References on Road Materials

1. Blanchard and others, American Highway Engineers Handbook, New York, 1919. (Wiley and Sons, Inc.) (Many references.) 2. Hubbard and Jackson, U. S. Dept. Agric., Bull. 537, 1917. (Tests of stones from different states.) 3. Lord, U. S. Dept. Agric., Office Pub. Roads, Bull. 3, 1916. (Examination and classification of Rock for Roads.) Also *Ibid.*, Bull. 348, 1916. 4. Reinecke, Econ. Geol., XIII, p. 557, 1918. (Non-bituminous road materials.) 5. Reinecke, Can. Geol. Surv. Mem. 99, 1918. (Good general discussion.) Special reports have also been issued by various state Geological Surveys, and by the Canadian Geological Survey.

CHAPTER XII

ORE DEPOSITS

Nature and Occurrence

Ore deposits. — The term *ore deposits* is applied to concentrations of economically valuable metalliferous minerals found in the earth's crust.

Ore. — This refers to those portions of the ore deposit which contain the metallic mineral or minerals in sufficient quantity and in the proper combination to make their extraction both possible and profitable.

Protore is a metalliferous rock not rich enough to mine, but which by natural secondary processes may become sufficiently enriched to be classed as ore.

Ore minerals are those minerals carrying the desired metallic contents which occur within the deposit. Thus galena and cerussite are ore minerals of lead; chalcocite, chalcopyrite, and azurite are ore minerals of copper; and magnetite and siderite are ore minerals of iron. An ore deposit may contain ore minerals of one or several metals or several ore minerals of the same metal.

Only a few elements, such as gold, copper, platinum, and mercury, occur in ores in the native form. In most cases the metal is combined with other elements, forming sulphides, hydrous oxides, carbonates, sulphates, silicates, chlorides, and phosphates. Some of these are restricted to the weathered portion of the ore deposit.

Gangue minerals. — These include certain usually common minerals, chiefly of non-metallic character, which are associated with the ore minerals, and which carry no values worth extracting. Quartz is the commonest, but calcite, barite, fluorite, and siderite are also common, while dolomite, hornblende, pyroxene, feldspar, rhodochrosite, etc., are found in some ore bodies.

The gangue minerals may be more or less intimately mixed with the ore minerals, or segregated in masses. In the former case, if there is sufficient difference in specific gravity between the ore and gangue minerals, the ore can be crushed, and the two often separated by mechanical concentration. In the latter, the masses of gangue can be avoided or thrown out in mining. If the ore is low grade, and both

ore and gangue minerals in a finely divided condition, leaching may be resorted to as the first step in separating the metal. If the metalliferous mineral is magnetic, a process of magnetic separation can be employed, as in the case of magnetite.

Origin of Ore Bodies

In an earlier paragraph, ore deposits have been referred to as natural concentrations. This being so, they must have been concentrated either at the same time as the enclosing rock (*contemporaneous* or *syngenetic* deposits) or else they have been formed by a process of concentration at a later date (*subsequent* or *epigenetic* deposits). Most ore deposits belong to the second group, and not a few to the first, but the origin of many is still in doubt.

Contemporaneous ore deposits. — These may occur in igneous or sedimentary rocks. Those found in igneous rocks are said to be due to magmatic segregation, the field evidence showing that they have been separated from the magma by this process (see also Chapter on Rocks). In such cases the ore grades into the surrounding rock; in others it is sharply separated from the igneous mass, reminding one of a dike, the supposition being that it represents a very basic segregation, which has been forced up from below, subsequent to the intrusion of the igneous rock itself, but not necessarily in all cases before the enclosing igneous mass had entirely cooled.

Most magmatic ores are usually associated with basic igneous rocks. Well-known examples of magmatic segregations are the titaniferous iron ores of the Adirondack Mountains, New York; and the Scandinavian iron-ore deposits of Kirunavaara and Luossavaara. Chromic iron ores are no doubt formed in this manner.

When the contemporaneous deposits are of sedimentary origin they may be either interstratified or surface deposits. The former have originated from processes similar to those which have formed the enclosing rocks. Some have accumulated by precipitation from sea water or fresh water by chemical or organic agencies, while others have had a mechanical origin, having been set free by the disintegration of rocks on the land, the grains being washed into the sea or valleys.

An excellent example of an interstratified deposit is the Clinton iron ore (hematite) found from New York to Alabama (Fig. 240). The iron ores of Wabana Island, Newfoundland, are also of this type.

Surface deposits of contemporaneous origin include the placer or gravel deposits so well known to the gold miner. They represent the heavier products of rock decay which have settled down usually in

stream channels, or in other cases have accumulated along sea beaches. If the formations from which they are derived contain metallic minerals of resistant character, such as gold, tin, platinum, etc., they become concentrated in the gravel deposit. The gold gravels of California and Alaska and the platinum gravels of the Urals are of this type.

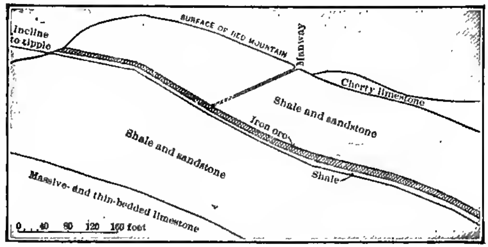


FIG. 240. — Section of Red Mountain, Birmingham, Ala., containing a bedded ore deposit of contemporaneous origin. (After Burchard, Amer. Inst. Min. Engrs., XL, 1910.)

Subsequent ore deposits. — In the formation of this type of ores the metallic compounds have been obtained from different rocks, but chiefly igneous ones, mainly through the agency of water usually of magmatic character, and deposited under favorable conditions. The following evidence confirms this belief:

It is a well-known fact that metallic minerals in small quantities are widely distributed through igneous rocks. They may also be found in sedimentary ones, since these were probably originally derived from the igneous rocks. But in spite of this widely recognized occurrence of metallic minerals in the rocks, few probably realize the small percentage existing outside of the concentrated portions of ore deposits, and the following table, which shows the average composition of the earth's crust, will make clear this point.[1]

AVERAGE COMPOSITION OF EARTH'S CRUST

Oxygen	47.33	Carbon	0.19
Silicon	27.74	Phosphorus	0.12
Aluminum	7.85	Manganese	0.08
Iron	4.50	Sulphur	0.12
Calcium	3.47	Barium	0.08
Magnesium	2.24	Chlorine	0.06
Potassium	2.46	Fluorine	0.10
Sodium	2.46	Strontium	0.02
Titanium	0.46	All others	0.50
Hydrogen	0.22		

The above figures make clear the interesting fact that, of some twenty metals which are of importance to us for daily use, only three, viz., aluminum, iron, and manganese, are included in the above list, and

[1] F. W. Clarke, U. S. Geol. Survey, Bull. 695, p. 35, 1920.

that the others except chromium and nickel must be present in amounts of less than 0.01 per cent.[1]

Mode of concentration. — There seems to be little doubt that water has served as the chief concentrating agent of subsequent ores, for the following reasons:

Water of either meteoric or magmatic origin is widely distributed through the rocks. Its solvent power is appreciable if it is alkaline or acid, and in addition if heated or under pressure. Both mine waters and hot springs show dissolved metallic compounds.

Most geologists now believe that in the majority of cases magmatic waters have been the primary concentrating agent of ore minerals, and that meteoric waters have effected the initial deposition in relatively few instances. They do however recognize that the surface waters have in many cases played an important rôle in the rearrangement and further concentration of ore deposits in or just below the zone of weathering.

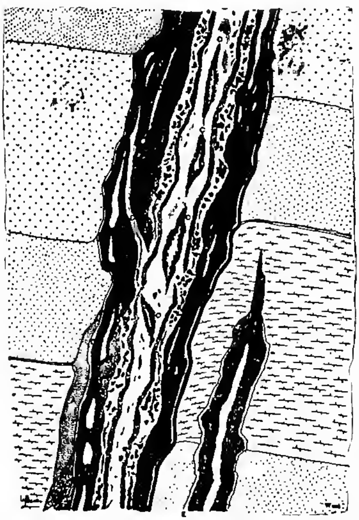


FIG. 241. — Vein filling a fault fissure. Enterprise mine, Rico, Col. (After Rickard, Amer. Inst. Min. Engrs., XXVI, 1897.) Shows irregular banding, also vugs in center of vein. White vein material is quartz; dark, is blende and rhodochrosite.

The importance of magmatic waters as agents of primary deposition is based on their greater depth of circulation, and also on the close association of many ore bodies with igneous rocks, which not only serve as a probable source of the metals, but give off water during cooling and consolidation.

Deposition of ores. — The deposition of ores from solution may occur either in cavities or by replacement.

Cavity deposition. — The cavities in which ores are deposited may be formed in different ways, and may occur in all kinds of rocks. Thus they may represent solution cavities in limestones, joint or fault fissures, and interspaces of a breccia, gas and shrinkage cavities in igneous rocks, the pores between the grains of a sedimentary rock, etc.

Precipitation of metals from solution. — If the metalliferous and other minerals were taken into solution at considerable depths where

[1] An earlier table published by Clarke gives nickel as 0.023 per cent and chromium as 0.033 per cent.

temperature and pressure were high, then as the waters rose towards the surface, where both of these were less, the decreasing solvent power of the solution would cause it to deposit some of the dissolved material. In other cases the deposition of the metals may have been due to the mingling of different solutions, resulting in chemical reactions which yielded insoluble compounds. The contact of solutions carrying sulphates, with carbon, organic matter, or other reducing agents, would reduce these to insoluble compounds such as sulphides, sulpharsenides, sulphantimonides, etc. Or, in other cases, the approach of a solution to the surface, where it is exposed to oxidizing conditions, could also cause precipitation, as, for example, the change of ferrous sulphate to hydrous ferric oxide.

Where precipitation takes place on the walls of a cavity, the ore and gangue minerals are sometimes built up layer upon layer (*crustified*). There is also a sharp boundary between ore body and wall rock.

Replacement. — Under favorable conditions mineral-bearing solutions may attack the minerals of the rock through which they move, dissolving them wholly or in part, and depositing other mineral compounds in the place of the mineral matter removed. This is known as *replacement* or *metasomatism*. In some cases the substitution is complete, as when calcite is removed and quartz is deposited; in others it is only partial, as when iron-bearing silicates are decomposed by sulphur-bearing solutions, and pyrite is formed, or when lime silicates replace lime carbonate.

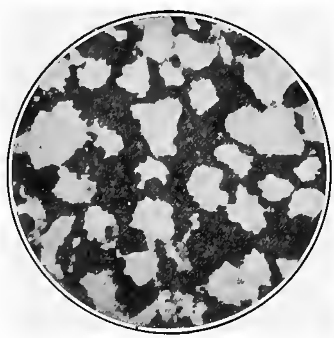


Fig. 242. — Photomicrograph of a section of quartz conglomerate, showing replacement of quartz (white) by pyrite (black) × 25 diam. (After Smyth, Amer. Jour. Sci., XIX, 1905.)

The ore-bearing solutions enter the rock along channels of access, and attack the minerals, penetrating first along cleavage planes or fracture lines, and then attacking the solid portion of the grains. The simplest and most common type of replacement is that of the calcium carbonate of fossils by silica, or by pyrite. Even though replacement may be complete, the original structure or even texture of the rock may be preserved. As an example of the latter we have silicified rhombs of dolomite.

Replacement is an important process in the formation of ore deposits. Certain rocks such as limestone are more easily replaced than shales or quartzites, but few rocks under proper conditions entirely

resist the process. Ferromagnesian minerals like hornblende are replaced more readily than the more acid silicates, such as feldspar.

The boundaries of replacement deposits are usually indefinite, but not necessarily so.

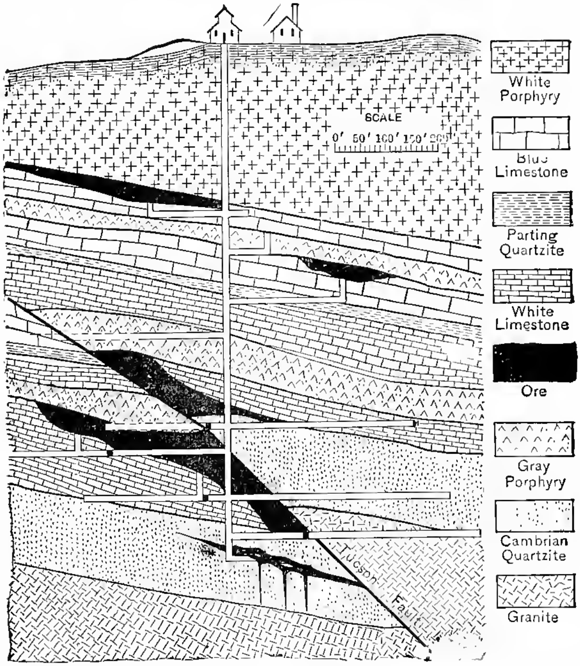


Fig. 243. — Section through the Tucson shaft, Leadville, Col., showing replacement ore bodies. (After Argall, Eng. and Min. Jour., LXXXIX, 1910.)

Physical conditions of ore deposition. — It has been pointed out that ore-bearing solutions are given off by igneous rocks, and that they move towards the surface, passing through zones of decreasing pressure, and gradually becoming cooler. Thus we see that there is a gradual change of physical conditions as we go towards the surface.

Starting with this hypothesis as a basis, and carefully studying all available evidence, we find that many different minerals appear to have a critical level. In other words, certain minerals can exist or form under certain conditions of temperature and pressure, but not under others. Some minerals, on the other hand, persist through a wide range of conditions.

Close to the igneous rock where pressure and temperature are sufficiently high to heat the water above its critical point (365° C.) it must be in a vaporous form, and the process of deposition under these con-

ditions is termed *pneumatolysis* (gaseous). If deposition occurs when the water is in a liquid form, it is termed *hydatogenesis* (aqueous).

We thus recognize a series of type deposits ranging from those formed close to an intrusive rock under conditions of high temperature and pressure to those formed remote from it and fairly close to the surface. These may be briefly referred to.

Pegmatite deposits. — These are formed under gas-aqueous conditions close to an intrusive rock, often of siliceous character and may occupy fractures in the intrusive itself or in the surrounding rock. They are not important as sources of ore, but are the chief primary sources of such metals as tin, tungsten, and bismuth. Topaz, tourmaline, and fluorite are common gangue minerals. The wall rocks are often strongly altered, the feldspar and mica especially being attacked by the water vapors carrying fluorine, and replaced by a mass of quartz, topaz, tourmaline, and lepidolite giving a rock type termed *greisen*. Cassiterite may be present in the wall rock as well as in the vein.

Contact-metamorphic deposits. — These include certain deposits found in some sedimentary rocks, chiefly calcareous ones, near their contact with igneous intrusions, especially those of a more or less acid character.

The ore deposits are a mixture of silicates and ore minerals. The former when occurring in limestone include garnet, wollastonite, epidote, diopside, amphibole, etc., while in shale or slate we find andalusite, sillimanite, biotite, etc.

The common ore minerals are oxides of iron, mixed with sulphides of copper. Lead and zinc are rare. Gold and silver may be present.

Since these contact-metamorphic deposits are formed sometimes in limestones which in their unaltered condition are practically pure calcium carbonate, it is quite evident that the foreign substances came from the igneous rock.

The deposits are somewhat bunchy in character and of irregular shape, and as a whole do not extend very far from the contact.

Among the important occurrences of this type may be mentioned the Morenci, Ariz., copper deposits, and those of Bingham Canyon, Utah, although here the main production of the camp now comes from the disseminated ore, found in the porphyry near its contact with the limestone.

Deep vein zone deposits. — These are mineralogically related to the contact-metamorphic deposits. They are usually tabular in form because of their association with fissures. They are therefore closely associated with intrusives. The deposits may carry gold, tin, zinc,

copper, and iron. They are not of great importance in the United States, but some gold ores of this type are of commercial prominence, as those of Lead City, S. Dak., and some in the southern Appalachians.

Intermediate vein zone deposits. — These form a most important group often associated with intrusives and chiefly of vein form. They show great mineralogical variety, and yield notable amounts of copper, gold, silver, lead, zinc, arsenic, and antimony. Complex sulphosalts of antimony and arsenic are common. The deposits of Butte, Mont., Cœur d'Alêne, Ido., and Cobalt, Ont., are of this type.

Shallow vein zone deposits. — The veins of this type are formed near the surface, that is from a few hundred to four or five thousand feet, this being shown by their occurrence in beds of relatively recent volcanic rocks.

The wall rock also shows strong alteration of sericitic (p. 333) or propylitic character (p. 332).

In shallow-formed veins, gold and silver are the prevailing ores, but the silver is usually relatively more abundant than it is in the deeper veins with quartz gangue. Like the deeper veins they may carry pyrite, galena, and sphalerite, but in addition chalcopyrite, arsenopyrite, argentite, and stibnite are characteristic ore minerals. Magnetite and specularite are absent.

Filling of open spaces is an important process. The Cripple Creek, Col., region is an example of this type of occurrence. Here the ore occurs chiefly as veins, in Tertiary volcanic rocks, which fill the throat of a volcano in older granites.

Other districts of this type are Tonopah and Goldfield, Nev.; the San Juan district of Colorado, etc. Cinnabar deposits also belong to this group.

Hydrothermal alteration. — The hot ascending solutions of varying composition often bring about a most profound alteration of the rocks which they traverse, extracting, it may be, certain elements and adding others. Indeed in many cases the alteration is so extensive that the rock bears no resemblance to its former self.

Alteration is usually most intensive along the fissures which conducted the solutions, but if the rock is extensively fractured it is affected over a large area.

The types of hydrothermal alteration which can be recognized are *propylitization*, *sericitization*, *silicification*, *greisenization*, and *alunitization*.

Propylitization. — This process results in a change of the dark silicates to chlorite, epidote, and pyrite, and of the feldspars to calcite, epidote, and quartz. The alteration is most often seen in rocks of intermediate or basic composition, and

the rocks so changed are usually of a greenish-gray color with bright greenish-yellow stains of epidote. Propylitization is specially prominent in volcanic rocks.

Sericitization. — This process changes the silicates of the rock to a fine grained mixture of sericite, calcite, quartz, and pyrite. Sericitization is a common type of hydrothermal alteration, which is common near veins, but may pass outward into propylitic alteration. The rocks so altered are white or light yellow in color, and the mass often appears clay-like. Indeed sericite masses are sometimes mistaken for kaolin.

Silicification. — This involves a replacement of the rock by silica. It is often noticed in igneous, metamorphic and sedimentary rocks, especially limestones.

The original structure of the rock may sometimes be clearly preserved. The schist carrying the disseminated copper ore at Miami, Ariz., for example, is strongly silicified.

Alunitization. — This is a somewhat rare type, produced, as at Goldfield, Nev., by the action of sulphuric acid solutions on feldspars. The alunite here occurs not only as a massive crystalline constituent of the altered rocks, but also intergrown with pyrite, gold, tellurides, and other minerals in the ore. The fragments of alunitized rock on the dumps give them a whitish appearance.

Greisenization. — The granite walls of many tin veins show a strong and characteristic alteration, the feldspar and muscovite being changed to a mass of quartz, topaz, tourmaline, and lepidolite, to which the name *greisen* is applied. Cassiterite may also be present in the altered wall rock.

Forms of Ore Bodies

Ore bodies vary greatly in form, and this character has sometimes been used as a basis for classification, instead of genesis which is more satisfactory. The following are the more important types.

Fissure veins. — A fissure vein can be defined as a tabular mineral mass occupying or closely associated with a fracture or set of fractures in the enclosing rock, and formed either by filling of the fissures as well as pores in the wall rock, or by replacement of the latter, or both. In some cases bands of the same minerals may be repeated on both sides of the fissure (crustified structure).

Replacement veins show great irregularity of width and usually lack well-defined boundaries; they do not, moreover, as a rule, show symmetrical banding, or breccias cemented by vein material.

The term *vein material* applies to the aggregate of materials which make up the ore body. A layer of soft, clayey material known as *gouge* or *selvage* sometimes forms between the vein and country rock, and may originate in crushing caused by movement along the vein walls. The ore sometimes follows certain streaks in the vein known as shoots (q.v.), or again it may be restricted to pockets of great richness known as *bonanzas.*

Fissure veins vary in width and persistence; splitting and intersecting veins are also known. If a vein is inclined, the lower wall is termed the *footwall* and the upper the *hanging wall.* *Lode* is a vein consisting of closely-spaced parallel fissures, sometimes accompanied by mineralization of the intervening rock. *Vein system* is a larger assemblage of vein fissures and may include several lodes. *Apex* is the term

applied to the top of a vein. It does not necessarily reach the surface, or even the top of the bed rock. *Bedded vein* is a term sometimes applied to a deposit conformable with the bedding, as in the Snowstorm mine, Cœur d'Alêne district, Idaho.

Chimney. — This is a term applied to ore bodies which are rudely circular or elliptical in horizontal cross-section, but may have great vertical extent; the Yankee Girl mine at Red Mountain, Col., is of this type.

Stock. — An ore body similar to a chimney but of greater irregularity of outline.

Fahlband. — A term originally used by German miners to indicate certain bands of schistose rocks impregnated with finely-divided sulphides, but not always rich enough to work. The Homestake ore body at Lead, S. Dak., is an example.

Disseminated deposits. — Types of ore deposits in which the ore minerals occur as small particles or veinlets scattered through the mineralized rock. Such deposits are sometimes of great size, and in some parts of the west form important sources of copper ore. They are found mostly in schists and intrusives, especially those which have been fissured or shattered. This of type ore is worked at Bingham, Utah; Clifton, Ariz., etc.

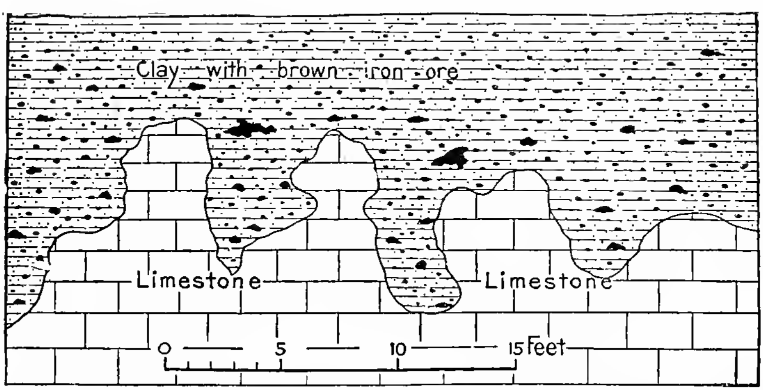


Fig. 244. — Vertical section showing structure of a residual deposit of brown ore, from Reed Island, Va. (After Harder, U. S. Geol. Survey, Bull. 380, 1909.)

Residual deposits. — In the case of some iron, manganese, lead, and zinc ores, the rock containing the primary ore has been weathered to a mass of residual clay (Fig. 244). During this process the metallic compounds have been changed to oxidized forms (p. 336) and concentrated in lumps and nodules, stringers or crusts, within the clayey mass. Many of the eastern limonites are of this type. So, too, are

some of the lead and zinc ores of Virginia, and the manganese ores of the southern states.

Ore shoots. — Few ore deposits are of uniform character throughout; indeed the occurrence of pay ore is apt to be more or less irregular, the richer ore being sometimes more or less localized. These richer pockets are commonly called *ore shoots,* and they usually owe their formation to some structural feature that has guided the ore solutions.

Primary and Secondary Ores

Primary ores are those which have remained practically unchanged by surface agencies since their deposition. Secondary ores are those which have been altered by surface agencies, especially descending meteoric waters. Unfortunately the two terms are not always used in exactly this sense.

Weathering and secondary enrichment. — Weathering has often changed an ore deposit in its upper part, and sometimes to a considerable depth, while the lower-lying portions below the groundwater level are often enriched by secondary processes. The lower limit of the zone of weathering may, however, be very irregular (Fig. 245).

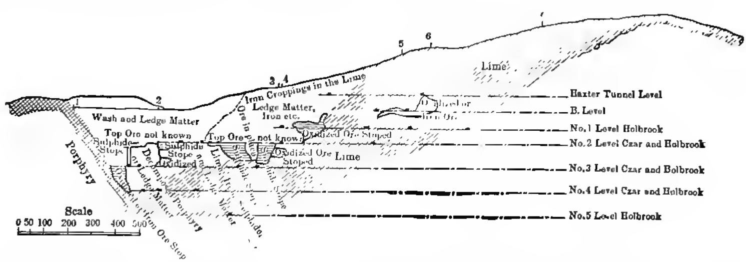


FIG. 245. — Section through Copper Queen mine, Bisbee, Ariz., showing variable depth of weathering. (After Douglas, Amer. Inst. Min. Engrs., Trans., XXIX.)

Zones in an ore body. — In passing downward from the surface the following zones may sometimes be distinguished, although they are not always separately recognizable in all ore bodies.

I. Zone of weathering (*a*) Surface zone of complete oxidation.
(*b*) Zone of complete leaching.
(*c*) Zone of oxide enrichment.
II. Zone of secondary sulphides.
III. Zone of primary sulphides (protore in many cases).

Zone of weathering. — Nearly all minerals are attacked by weathering agents, but the metallic minerals are more easily attacked and more profoundly affected than the non-metallic ones.

The weathering processes involve both chemical and physical changes, but the chemical reactions especially are more intricate in ores than they are in the country rock. As a result of weathering, worthless minerals may be removed, leaving the weathered part more porous, so that the richness may be increased, because we have a greater quantity of metals per ton of rock. On the other hand, weathering through solution may remove some of the metallic compounds, leaving the upper part of the ore body impoverished.

The first process in weathering is the breaking down of insoluble sulphides, which takes place above the water level, changing them first to sulphates and in some cases finally to oxides or other compounds.

Without going into the details of the chemistry of weathering (see Refs. 4, 5, 7) a few common products formed by the weathering of different metallic minerals may be noted.

Primary ore	Weathering products of more or less insoluble character.
Pyrite	Limonite.
Copper sulphides	Copper silicate, carbonates, oxides.
Lead sulphide	Lead sulphate, carbonate.
Zinc sulphide	Zinc silicate, carbonates.

The change is not always as direct as the above would seem to indicate an intermediate sulphate being usually formed first, and this may be sometimes carried down below the water level before it undergoes further change. In the upper zone of the belt of weathering, oxidation has been carried to an extreme, and at the surface there is frequently an *iron cap* or *gossan*, composed of limonite and hydrated hematite, often with much residual silica. It may also carry residual gold, silver chloride (in arid regions), or even weathered compounds of lead, zinc, and copper; provided of course these metals are present in the primary ore.

Below this zone may follow one which is more or less thoroughly leached. Then in the lower part of the belt of weathering, or just above the sulphide zone, the minerals are sometimes only partly oxidized, forming oxides, carbonates, silicates, and native elements. Sometimes rich oxidized ores are found in this zone, especially where the wall rock is limestone.

Secondary sulphide zone. — In many ore bodies, rich masses of ore occur below the oxidized zone, which are of secondary character, or there may be a zone of ore which, if not rich, is at all events richer than the primary ore. This is seen most often in copper, gold, and silver, and to a less extent in lead and zinc ores.

It is due to the soluble products of weathering being carried below the water level, where they (sulphates) react with sulphides and are again reduced to sulphides.

This is known as secondary enrichment,[1] and many important ore bodies, such as most of the copper deposits of the West, owe their workable character to this enriching process.

The two following equations may be taken as illustrative of the reactions which occur in this zone, the sulphate in both cases having been derived from the weathered zone above in solution.

$$7\,ZnSO_4 + 4\,FeS_2 + 4\,H_2O = 7\,ZnS + 4\,FeSO_4 + 4\,H_2SO_4$$

or

$$14\,CuSO_4 + 5\,FeS_2 + 12\,H_2O = 7\,Cu_2S + 5\,FeSO_4 + 12\,H_2SO_4.$$

Evidence of this process can be seen to advantage in some copper deposits, where in the secondary sulphide zone rims of chalcocite surround grains of pyrite. (Fig. 246.)

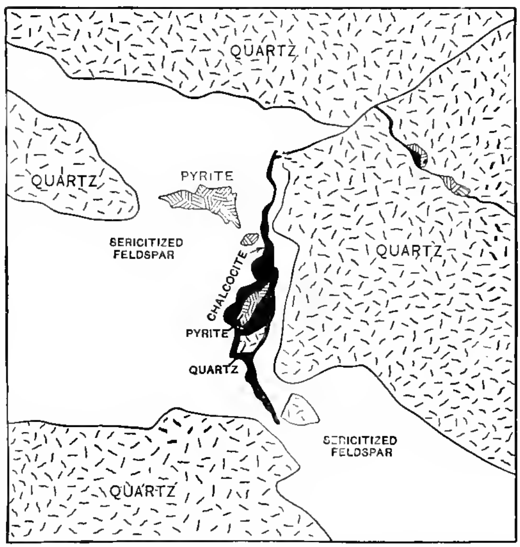


Fig. 246. — Section of ore showing precipitation of secondary chalcocite on pyrite. (After Paige, U. S. Geol. Survey, Bull. 470, 1911.)

Since the position of the secondary sulphide zone is thought to be determined by the level of the water table, it may vary from a few feet in depth to several hundred feet in semi-arid and elevated regions, or in exceptional cases even deeper. Moreover, the thickness of the zone is extremely variable, for the process is affected by various conditions.

If the ore body below the water level is dense (impervious) and unfractured the downward migration of the metals is stopped. Secondary enrichment may also be lacking in arctic regions where the frozen ground prevents downward seepage.

[1] It is sometimes called downward secondary enrichment to distinguish it from what may be called upward secondary enrichment, as when a vein is reopened by fracturing and more metalliferous minerals deposited by solutions rising from below.

Change of ore with depth. — It has been pointed out that all metallic minerals do not weather with equal rapidity, consequently some may be carried downward more rapidly than others. Thus zinc sulphide weathers more rapidly than lead sulphide, resulting sometimes eventually in an ore deposit which yields chiefly lead above and zinc below. By the operation of similar processes, we may have developed from a copper-gold ore, a gold deposit above and an auriferous copper deposit below.

Gold is leached under favorable conditions. When held in solution as chloride, it is precipitated by ferrous sulphate unless an oxidizing agent, such as manganese oxide, is present, in which case it remains in solution. Gold may, therefore, be carried in an acid solution so long as the higher oxides of manganese are present. The precipitation of the gold from chlorine solution may be caused by native metals, sulphides, organic matter, and other materials.

Zone of primary sulphides. — The boundary between the secondary sulphide zone and that of primary sulphides next below is very irregular and often somewhat indefinite. The primary ore is often too low grade to work. Sections of the ore when examined under the microscope sometimes show that more than one ore mineral has been deposited at a time.

Outcrops of ore bodies. — Many ore bodies outcrop on the surface. Where the ore is more resistant than the wall rock it may stand out in more or less strong relief, and where it is less resistant than the country rock it weathers more rapidly. In the latter case, its presence might be indicated by a depression. Veins with predominant quartz are usually resistant, while those with predominant sulphides are likely to be the reverse. Strong persistent fissure veins on the surface are not unlikely to continue so with depth, but small, narrow, branching veins are less reliable.

If a vein outcrops on a steep hillside, the creep of the surface material will carry fragments of the outcropping ledge down the slope. These become mixed with the surface material and are termed "*float.*"

Silicified ledges and limonite gossans sometimes form prominent outcrops.

Distribution of Ore Deposits in the United States

A map showing the distribution of ore deposits in the United States at once conveys the idea that the useful and precious metals are not uniformly distributed; indeed one is impressed with the predominant variety of metals found in the western states and the practical absence

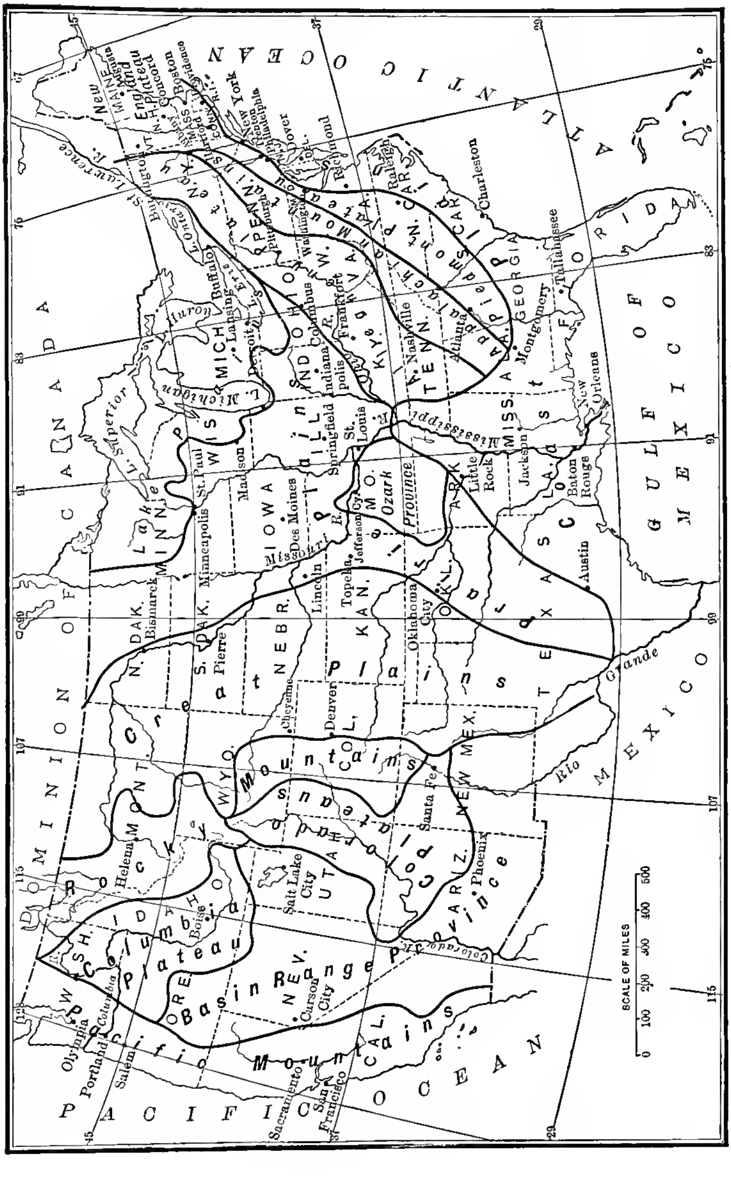


FIG. 247. — Map of United States showing physiographic provinces. (After Ransome.)

of them in the region of the Great Plains. Their general occurrence in the several physiographic provinces (Fig. 247) may be briefly referred to.

Coastal Plain. — This province contains practically no metalliferous deposits of commercial importance, even though the belt is rich in non-metallic substances, such as clays, sands, phosphates, and marls. Some bauxite is mined in the coastal plain of Georgia.

Piedmont Plateau. — A number of metalliferous deposits of iron, copper, manganese, and gold with some silver, lead, and zinc are found in the ancient crystalline rocks of this belt, but since most of them are chiefly of historic interest, they add with few exceptions little to the total production of the United States.

Most prominent among these are the magnetites of southeastern Pennsylvania and the states farther south, and the gold and copper ores of the southern states. The only productive deposit of titanium ore is located in this belt.

Appalachian Province. — This belt is of importance in the metal-mining industry as it carries deposits of bedded (Clinton) iron ore, residual brown iron ores, and manganese, as well as the copper deposits of Tennessee, and the lead and zinc ores in Virginia and Tennessee. The bauxite deposits of the Georgia-Alabama-Tennessee district also lie in this province.

Allegheny Plateau. — With the exception of the magnetite deposits of the Adirondack Mountains, which rise above the plateau at its northern end in New York state, there are few metalliferous deposits of importance in this province.

Prairie Plains. — This is an exceedingly important province locally for it contains the vast iron deposits of the Lake Superior region, the native copper deposits of Keweenaw Point, Mich., and the lead and zinc deposits of the upper and lower Mississippi Valley region. Outside of these districts few metals have been found.

Great Plains. — With the exception of the isolated mass of rocks forming the Black Hills of South Dakota, which contain gold ores, and the mercury area of Brewster County, Texas, the province is singularly free from metalliferous deposits.

Cordilleran Region. — This area includes the provinces known as the Rocky Mountains, Colorado Plateau, Columbia Plateau, Basin Ranges, and Pacific Mountains.

In the Rocky Mountains province which consists of mountain ranges and high peaks, with many igneous rocks, a number of valuable ore deposits are found. These include the gold deposits of Cripple Creek, Col., the lead and zinc ores of Leadville, Col., the lead-silver ores of

the Cœur d'Alêne district, Idaho, etc. Copper also occurs associated with other ores.

Not less important is the Basin Range province. This contains important gold and silver ores, associated with recent volcanic rocks, as at Goldfield, Tonopah, and Virginia City, Nev. In this same province also are found the enormous deposits of disseminated copper ores obtained at Bingham, Utah; Ely, Nev.; and Miami, Ray, and Ajo, Arizona.

The Pacific Mountain province is chiefly important as a source of gold quartz ores, such as the Mother Lode of California, and gold-bearing gravels. Mercury has been found at scattered points in the southern part of the province, and iron ore in the northern portion.

Chromite deposits are worked in California and Oregon.

Occurrence of the More Important Ore Types

Iron Ores

In spite of the abundance of iron in the rocks of the earth's crust, there are few ore minerals of the metal. The iron ores of the greatest commercial value are those which occur in great quantity, are favorably located, and are easily mined.

The quantity of iron ore mined annually in this country is large, and the average grade is higher than that obtained in many other countries, so that if we include our deposits of medium grade the country contains large ore reserves.

Iron-ore minerals. — The ore minerals of iron, together with their composition and theoretic percentage of metallic iron, are:

Name.		Composition.	Per cent, iron.
Magnetite.	Magnetic iron ore	Fe_3O_4	72.4
Hematite.	Specular iron ore, red hematite, fossil ore, Clinton ore	Fe_2O_3	70.0
Limonite.[1]	Brown hematite, bog iron ore, ochre	$2\,Fe_2O_3 \cdot 3\,H_2O$	59.80
Siderite	Spathic ore, carbonate ore, black-band, clay iron stone, kidney ore	$FeCO_3$	48.27

[1] The group name *brown ore* is perhaps preferable as the ore may contain other hydrous oxides.

Pyrite, a very common mineral, can only be used as an ore after the sulphur has been expelled by roasting. Its chief use is for sulphuric-acid manufacture, although the "blue-billy" iron residue after desulphurizing is used to some extent for the manufacture of pig iron.

Few ores of iron approach in richness the theoretic percentage shown above, the deficiency in iron content usually shown being due to the

presence of a variable amount of gangue minerals. The impurities which they supply are alumina, lime, magnesia, silica, titanium, arsenic, copper, phosphorus, and sulphur, of which the last six produce a weakening effect on the iron.

Silica occurs in practically all ores in variable amounts, and is always high in residual limonites, which may likewise show high alumina. Pyrite is a common source of sulphur. Manganese, when present, is found mostly in limonite ores, and for certain purposes is desirable. It is also prominent in some Lake Superior ores. Apatite yields the phosphorus. Titanium is prominent chiefly in certain magnetites.

FIG. 248. — Map showing distribution of hematite and magnetite in the United States. (After Harder, U. S. Geol. Survey, Min. Res., 1907.)

Types of iron-ore deposits. — Iron-ore bodies are of varied form, but many of the important ones known in this country are lens- or basin-shaped in outline. They may be classified as follows:

1. Magmatic segregation deposits, usually of irregular form, but sometimes dike-like in character. The ore mineral is usually magnetite, and those found in basic igneous rocks are commonly titaniferous. The ore bodies at Lake Sanford, Adirondacks, are of the latter type. Those at Mineville, New York, and northern New Jersey are non-titaniferous.

2. Contact-metamorphic deposits commonly of somewhat pockety form, but the pockets often large. They carry both magnetite and hematite, and even a little copper. Fierro, N. Mex.; Iron Springs, Utah; and Cornwall, Pa., are in this class.

FIG. 249. — General view of Mountain Iron mine, Mesabi Range, Minn., showing mining of ore with steam shovels and covering of glacial drift (*a*). (Crandal and Maher, photo, from Ries' Economic Geology.)

3. Sedimentary ores of bedded character, the ore mineral being hematite, siderite or even limonite (bog ores). The Clinton hematite extending from New York to Alabama, and most extensively worked at Birmingham, Ala., belongs here. (See also p. 326.) Bog ores are of little importance, and bedded siderites yield but a small amount.

4. Ores concentrated by meteoric waters from protore and deposited as replacements in different kinds of rocks. The extensive deposits of hematite found in the highly folded and metamorphosed rocks of the Lake Superior region fall in this group (Fig. 249).

5. Residual deposits, as nodules or crusts in residual clays, the ore mineral being limonite or other hydrous iron oxides. They form an important type of ore in the Appalachian belt of Virginia and Alabama.

6. Lenticular masses in metamorphic rocks, of variable origin, the ore mineral being either magnetite or pyrite.

7. Gossan ores, as the limonite capping of many sulphide ore bodies. These are common in many parts of the West, but may be worked more for their precious metal contents than for the iron in them.

FIG. 250. — Map showing distribution of limonite and siderite in the United States. (After Harder.)

Copper Ores

Ore minerals of copper. — While the total number of ore minerals of copper is considerably larger than those of iron, not many of them are of widespread importance. Unlike iron, the ore minerals of copper are found associated with many different metals under a variety of

conditions. Indeed, such low-grade ore bodies as are mined can only be worked economically on a large scale.

The following are the ore minerals of copper, the more important ones being italicized.

Ore minerals.		Composition.	Per cent, Cu.
Unweathered zone	*Chalcopyrite*	$CuFeS_2$	34.5
	Chalcocite	Cu_2S	79.8
	Bornite	Cu_5FeS_4 [1]	63.3
	Enargite	Cu_3AsS_4	48.00
	Covellite	CuS	66.5
	Tetrahedrite	$Cu_8Sb_2S_7$	52.06
	Tennantite	$Cu_8As_2S_7$	57.00
	Native copper	Cu	100.00
Weathered zone	*Azurite*	$2\ CuCO_3,\ Cu(OH)_2$	55.10
	Malachite	$CuCO_3,\ Cu(OH)_2$	57.27
	Chrysocolla	$CuSiO_3,\ 2\ H_2O$	36.06
	Cuprite	Cu_2O	88.8
	Melaconite	CuO	79.84
	Brochantite	$CuSO_4,\ 3\ Cu(OH)_2$	62.42
	Atacamite	$Cu(OH)Cl,\ Cu(OH)_2$	59.45
	Chalcanthite	$CuSO_4,\ 5\ H_2O$	25.4

[1] Exact composition in doubt.

The difference in the nature of the copper compounds found in the weathered and unweathered zones is quite noticeable.

Most of the copper ores now worked are of low grade, that is as low as 2 per cent or less of copper, but they can be profitably treated because of the extent of the operations, and the possibility of concentrating them, if the ore minerals are sulphides.

The presence of other ores often increases the complexity of the smelting process, but with modern methods the several metals are separated and saved, and the impurities removed.

Copper-ore bodies are extensively affected by weathering. That portion of the ore body above water level may be either a limonitic gossan, from which most of the copper has been leached, or it may contain oxidized ores. By leaching, the copper may be transferred below the water level and re-deposited; indeed, were it not for the process of secondary enrichment having taken place, many a copper deposit in the southwest would not be workable. The secondary sulphide is often chalcocite.

Types of copper-ore bodies. — Copper ores have been formed at different periods in the geologic past, but the majority of them show an intimate association with igneous rocks. Five important types of occurrence may be referred to, all of which appear to have been formed

by magmatic waters, no important magmatic segregation deposits being known in the United States.

Contact metamorphic deposits. — These are found in crystalline, usually garnetiferous, limestone, along igneous contacts, and are known at several points in the West, including the Clifton-Morenci and Bisbee districts of Arizona, Bingham Canyon, Utah, etc. These were of some importance, especially in former years, but they have been outranked by the next type which is often associated with them.

Disseminated deposits. — Bodies of sulphides, deposited by magmatic waters, in igneous rocks or schists, either in connection with the preceding type or alone, form a type which has become of great importance in the West. The country rock is more or less fractured, and the low-grade disseminated ore is sometimes present in large amounts. Its commercial value is due to secondary enrichment, and over it there is a leached capping of variable thickness. Since these ores often occur in porphyritic igneous rocks, they are sometimes called *porphyry coppers.* This disseminated type is worked at Ely, Nev.; Bingham, Utah; Miami, Ray, Ajo and Clifton-Morenci, Ariz., etc.

Vein deposits. — In some districts, as Butte, Mont., the copper ore is found in fissure veins, in which it has been deposited either by replacement or cavity filling. The wall rock is often strongly altered by hydrothermal metamorphism. Other metals may be present in variable amounts.

A modification of this type is found in the Michigan area, where native copper occurs in amygdaloidal volcanics, sandstones, and conglomerates, either as a replacement, or filling cavities. This occurrence is unique among those of the United States, but a similar type is found in New Jersey, and its analogue in Arctic Canada.

Vein deposits of mixed character, in which the copper is associated with lead, zinc, gold or silver, are worked at a number of points in the Rocky Mountains. Copper veins, with or without gold, are found at several points in the southern Appalachians. The Virgilina, Virginia-North Carolina, district is typical of the former type, and the Gold Hill, N. C., district of the latter.

Lenses in schists. — Lens- or pod-shaped deposits of chalcopyrite, with or without pyrite or pyrrhotite, are found in some metamorphosed schistose rocks. These deposits, which are usually of low grade, may represent replacements of metamorphic rocks along fissures, replaced limestone, or in some instances they are thought to be metamorphosed contact-metamorphic deposits.

They are worked at Ducktown, Tenn.; and the same type has been found at a number of other points in the Appalachian states from Ver-

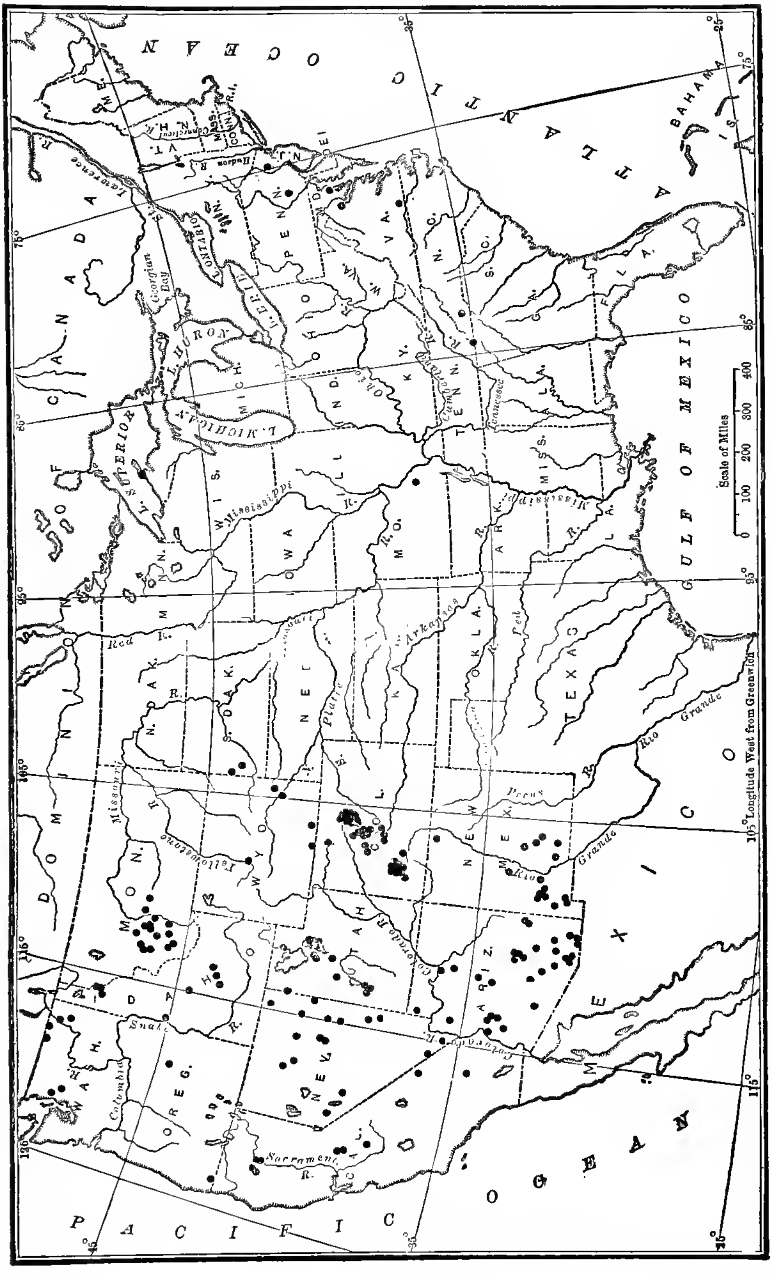


FIG. 251. — Map showing distribution of copper ores in United States. (From U. S. Geol. Survey.)

mont to Alabama, but are usually of low grade, owing to the large amount of pyrrhotite and pyrite and a small percentage of chalcopyrite. Similar occurrences consisting of a low-grade mixture of chalcopyrite and pyrite are worked in Shasta County, Cal.

Lead and Zinc Ores

These two metals are frequently associated with each other, and in the Rocky Mountain region, especially, gold, silver, and copper may be common associates.

Ore minerals of zinc. — The important ones are:

Name.	Composition.	Per cent, Zn.
Sphalerite	ZnS	67.0
Smithsonite	$ZnCO_3$	51.96
Calamine	$2\ ZnO,\ SiO_2,\ H_2O$	54.20
Hydrozincite	$ZnCO_3.2\ Zn(OH)_2$	60.0
Zincite	ZnO	80.3
Willemite	$2\ ZnO,\ SiO_2$	58.5
Franklinite	$(FeMnZn)O.(FeMn)_2O_3$	variable

The first of these may be either a primary or secondary enrichment ore, while the following three are found in the weathered zone. The last three are found in commercial quantity only at Franklin Furnace, N. J.

The sphalerite (known also as blende, jack, rosin jack, or black jack) is by far the most important ore of zinc. It is often associated with other sulphides, especially galena, pyrite, and marcasite, but more rarely chalcopyrite. Both smithsonite and calamine may occur in the same deposit; they are sometimes of crystalline form, but more often quite impure and of crusted or earthy character.

Ore minerals of lead. — These are as shown below:

Name.	Composition.	Per cent, Pb.
Galena	PbS	86.4
Cerussite	$PbCO_3$	77.5
Anglesite	$PbSO_4$	68.3
Pyromorphite	$Pb_3P_2O_8+\frac{1}{3}PbCl_2$	76.36

Galena is the commonest lead mineral and may be either primary or due to secondary enrichment. In complex ores it frequently carries silver. The other three minerals occur in the weathered zone, and of these cerussite is the most often found.

Weathering of lead and zinc ores. — Sphalerite weathers rapidly, and is leached out before the galena; not that the galena does not start to alter as soon, but because it becomes covered with an insoluble weathered product, which protects the sulphide. As a result of this differential leaching the zinc may all be removed from the upper part of a mixed lead and zinc ore body. The ore will consequently change from lead above to predominant zinc below. However, both lead and zinc ores may show secondary enrichment.

FIG. 252. — Map showing distribution of lead and zinc ores. (After Ransome, Min. Mag., X.)

Classification of lead and zinc ores. — On a mineralogical basis lead and zinc ores can be divided into three groups as follows:

1. Lead and zinc ores, practically free from copper and the precious metals. 2. Lead and zinc ores, carrying more or less gold and silver as well as some iron and copper. 3. Lead-silver ores.

In the first group, lead and manganese are not uncommon impurities, and those of southwestern Missouri carry small quantities of cadmium, calcite, dolomite, and pyrite or marcasite as common gangue minerals, while barite or fluorite may also be present.

The second group is found chiefly in the Rocky Mountains, and is not only of complex character, but differs in form and origin from the eastern deposits. Quartz is the common gangue mineral, while arsenic, antimony, and iron are common impurities.

The third group is confined to the western states, and carries small amounts of zinc, gold, and iron, in addition to the main constituents, lead and silver.

Mode of occurrence of lead and zinc ores. — Lead and zinc ores may occur under several different conditions as follows:

1. As true metalliferous veins, in igneous or stratified rocks, and with or without other metals. This type is prominent in the Cordilleran region.

2. Irregular masses in metamorphic rocks, as at Franklin Furnace, N. J. These supply zinc alone.

3. As irregular masses or disseminations, formed by replacement or impregnation in limestones or quartzites. Replacement masses in quartzite and limestone are found at Leadville, Col.; disseminated ores of lead in limestone, in the southeastern Missouri district, and of zinc with some lead in limestone, in southwestern Virginia and eastern Tennessee.

4. Contact metamorphic deposits. The occurrence of lead and zinc in these is usually subordinate.

5. In cavities not of the fissure-vein type, as the zinc ores of southwestern Missouri, and the lead and zinc ores of Wisconsin.

6. In residual clays, as in southwestern Virginia and eastern Tennessee.

Gold and Silver Ores

Ore minerals. — Gold and silver are obtained from a variety of ores, in some of which gold predominates, in others silver, while in still a third class the two metals may be mixed with the baser metals, lead, copper, zinc, and iron. In some ores even rarer elements, like arsenic, bismuth, tellurium, etc., are present.

Gold is found in nature chiefly as native gold, or as telluride. In the former case it may be visible, or mixed with pyrite, chalcopyrite, sphalerite, pyrrhotite, or arsenopyrite. Native gold may occur in both primary and secondary zones, but the telluride is always primary.

Silver, if in the native form, may be visible, or locked up mechanically in other sulphides, especially galena. Aside from this both primary and secondary ore minerals are found as below:

Name.		Composition.	Per cent, Ag.
Primary or secondary	Argentite	Ag_2S	87.1
	Pyrargyrite, ruby silver	Ag_2S, Sb_2S_3	59.9
	Proustite, light ruby silver	$2\ Ag_2S.As_2S_3$	65.5
	Stephanite, brittle silver, black silver	$5\ Ag_2S.Sb_2S_3$	68.5
Weathered zone	Cerargyrite, horn silver	$AgCl$	75.3
	Bromyrite	$AgBr$	57.4
	Embolite	$Ag(ClBr)$	64.5
	Iodyrite	AgI	46.0

Tetrahedrite (*see* under copper ore minerals) may also carry silver, replacing some of the copper, and its presence in the ore is regarded as a favorable indication.

Occurrence of gold and silver ores. — Most of the gold and silver mined in the United States is obtained from fissure veins, or similar deposits of irregular shape, and in which the ores have been deposited either from solution in cavities or by replacement. Much gold and a little silver are obtained from gravel deposits, and some contact metamorphic deposits are known. While gold has been found occurring as an original constituent of igneous rocks, this source is not to be regarded as being of commercial value.

It can be stated in general terms that the mode of occurrence of these two metals is quite variable, and although the fissure-vein type of deposit predominates, these fissures may form in any kind of rock, or along the contact between two different kinds.

The gold- and silver-bearing fissure veins include two prominent types, namely: (1) Quartz veins, and (2) propylitic veins, characterized by propylitic (p. 332) alteration of the wall rock.

Quartz-vein type. — This type which is characterized by quartzose ores with free gold and auriferous sulphides extends from Lower California, along the Pacific Coast to the Canadian boundary, and is also found along the Alaskan Coast. The deposits of the Mother Lode belt in California, and the Nevada City district of the same state, are of this type, as are also the gold veins near Juneau, Alas. Other gold-quartz veins, although of older age, occur in the Black Hills, S. Dak., and in the southern Appalachian states, but both these occurrences are sometimes more of the nature of impregnations in quartzose schists than well-defined veins.

Propylitic veins. — These represent an important type associated with lavas of Tertiary age, the veins being sometimes entirely within the volcanic rocks. The ores are usually quartzose, and while either gold or silver may predominate, the amounts of the two metals may be the same. Other metals may be present, but not necessarily in large amounts. The well-known mining camp of Cripple Creek, Col. (where the gold and silver are combined with tellurium), and the Goldfield and Tonopah districts of Nevada, are of this type.

Auriferous gravels. — These yield a large percentage of the gold production of the United States and Alaska. Their mode of origin has already been referred to on page 327, and they are found chiefly in those areas in which auriferous quartz veins are prominent. Hence, they are somewhat widely known in the Cordilleran region, the Black Hills, and in the South Atlantic states. Their greatest development, however, is along the Pacific Coast from California to Alaska.

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Areal Reports. — To list all of these, even the important ones, would be beyond the scope of this book.

Attention may be called to the fact that the Geological Surveys of New York, New Jersey, Virginia, North Carolina, Georgia, Alabama, Michigan, Arkansas, Missouri, Wisconsin, Minnesota, Oklahoma, Colorado, and California have issued a number of special reports.

In addition to these a number of bulletins and other special reports have been published by the U. S. Geological Survey, dealing especially with ore-bearing districts in the western United States.

APPENDIX

GEOLOGIC COLUMN

The earth's crust is made up of igneous, sedimentary, and metamorphic rocks. The igneous rocks may represent in part a portion of the original crust, formed at the time of its early cooling, and in part intrusive or extrusive materials forced up from below during different periods in the earth's history.

The sedimentary rocks are those which have been laid down on the ocean floor, on the bottom of inland seas or lakes, or to a less extent on land throughout the vast period of geologic time. They often contain the impressions, or even remains of animals and plants which lived in the past. These imbedded remains (fossils) are of great service to the geologist in determining the age of the inclosing rocks. The age of the non-fossiliferous rocks of whatever kind (igneous, sedimentary, and metamorphic) is determined where possible by their structural relationship to other rocks of known age.

The divisions and subdivisions of geologic time are not yet absolutely fixed, and the minor subdivisions established, even for one part of a continent, may not agree with those of another part, due chiefly to the fact that continuous deposition of sediment might be going on in one area, while in another, during the same time, the land was above sea level, and there was no sedimentation. In some cases the thickness of the sedimentary rocks deposited without break over a given portion of the earth's surface may amount to many thousand feet.

The names applied to the divisions of geologic time and to the rocks are not the same, but for each division of the one there is a corresponding one of the other. The names adopted by the International Geological Congress for the time and rock scales are:

Time Scale	*Rock Scale*
Era	Group
Period	System
Epoch	Series
Age	Stage

Thus we speak of the Silurian Period of time, but the rocks of that period are referred to as belonging to the Silurian System.

We give below a list of the major divisions of geologic time and their more important subdivisions, arranged in their order of formation, the youngest being at the top.

Cenozoic	Quaternary	Recent	
		Pleistocene or Glacial	
	Tertiary	Pliocene	
		Miocene	
		Oligocene	
		Eocene	
Mesozoic	Cretaceous	Upper or Cretaceous Proper	
		Lower or Comanchean	
	Jurassic		
	Triassic		
Palæozoic	Permain		
	Carboniferous	Pennsylvanian (upper)	
		Mississippian (lower)	
	Devonian	Upper	Chautauquan
			Senecan
		Middle	Erian
			Ulsterian
		Lower	Oriskanian
			Helderbergian
	Silurian	Cayugan (upper)	
		Niagaran (middle)	
		Oswegan (lower)	
	Ordovician	Cincinnatian (upper)	
		Mohawkian (middle)	
		Canadian (lower)	
	Cambrian	Saratogan (Croixian) (upper)	
		Acadian (middle)	
		Georgian (lower)	
Proterozoic (Algonkian)	Keweenawan	Lake Superior district	
	Upper Huronian (Animikian)		
	Middle Huronian		
	Lower Huronian		
Archæozoic	Archæan		

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